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Strategies for parametric design in architecture.

An application of practice led research.

Roland Hudson
A thesis submitted for the degree of Doctor of Philosophy
University of Bath
Department of Architecture and Civil Engineering
2010

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Roland Hudson

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Abstract

Strategies for parametric design in architecture.

An application of practice led research.

A new specialist design role is emerging in the construction industry. The primary task related to this role is focused on the control, development and sharing of geometric information with members of the design team in order to develop a design solution. Individuals engaged in this role can be described as a parametric designers. Parametric design involves the exploration of multiple solutions to architectural design problems using parametric models. In the past these models have been defined by computer programs, now commercially available parametric software provides a simpler means of creating these models. It is anticipated that the emergence of parametric designers will spread and a deeper understanding of the role is required.

This thesis is aimed at establishing a detailed understanding of the tasks related to this new specialism and to develop a set of considerations that should be made when undertaking these tasks. The position of the parametric designer in architectural practice presents new opportunities in the design process this thesis also aims to capture these.

Developments in this field of design are driven by practice. It is proposed that a generalised understanding of applied parametric design is primarily developed through the study of practical experience. Two bodies of work inform this study. First, a detailed analytical review of published work that focuses on the application of parametric technology and originates from practice. This material concentrates on the documentation of case studies from a limited number of practices. Second, a series of case studies involving the author as participant and observer in the context of contemporary practice. This primary research of applied use of parametric tools is documented in detail and generalised findings are extracted.

Analysis of the literature from practice and generalisations based on case studies is contrasted with a review of relevant design theory. Based on this, a series of strategies for the parametric designer are identified and discussed.

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Chapter 1

Introduction

This thesis begins with the assertion that all design is parametric. Design begins with the conscious or unconscious attribution of values to parameters describing functional requirements of the object and the constraints that limit the range of possible design solutions. As the design progresses further parameters are introduced describing the dimensions of the object and potentially physical properties to be used for its construction. The term *parametric design* is used in this thesis to mean the use of a computer to automatically modify a design as the values of parameters change and to make corresponding changes to the computer models during the design process.

1.1 Background

The research presented is practice led and sponsored jointly by Bentley Systems (2008) and the Engineering and Physical Sciences Research Council (EPSRC, 2008). Bentley's interest in the project is related to the development of a parametric design software package called GenerativeComponents (GC). At the time of commencing this research, this software was under development and it has subsequently been commercially released. The original goals were to investigate the educational implications of the availability of this software. The author's commitment to Bentley was to undertake a fixed number of days working with educational establishments and industrial practices throughout Europe and the United

States (figure 1.1) to assist individuals in the use and learning of GC. Details of these commitments are shown in figures A.1 and B.1 in the appendix.

This thesis is a response to observations that have developed in the course of undertaking this work. The commitment to Bentley Systems has been related to a specific software, it is the author's view that the findings have broader implications extending into a more general field of parametric design.

1.2 What is parametric design?

In order to gain an understanding of what parametric design means it is helpful to look briefly at definitions of ”parametric” and ”design” independently. “Parametric” is a derivative of “parameter” which itself originates from the greek *para*, meaning a subsidiary or beside and *metron*, as in to measure (OED, 2002). In mathematics a parameter is defined as ‘a quantity constant in the case considered but varying in different cases’.

Mathematically a particular circle can be described with two equations where there is one parameter, the angle θ, and one constant the radius r:

$x = r\cos\theta$

$y = r\sin\theta$

However if r is a parameter we have a potential family of circles with different radii.

Other definitions describe parameter as ‘a (esp. measurable or quantifiable) characteristic or feature’ or ’a constant element of factor (esp. serving as a limit or boundary)’(OED, 2002). A summary of these dictionary definitions provides a meaning used in this thesis; a parameter can be regarded as any measurable factor that defines a system or determines its limits.

A short but helpful dictionary definition of “design” is ’the art or action of producing a plan or drawing’ (OED, 2002). Expanding on the idea that design is some kind of process, literature reviewed in more detail later in this thesis provides further meaning of the term “design”. Simon (1996) describes a Science of Design as that which involves any process where a new

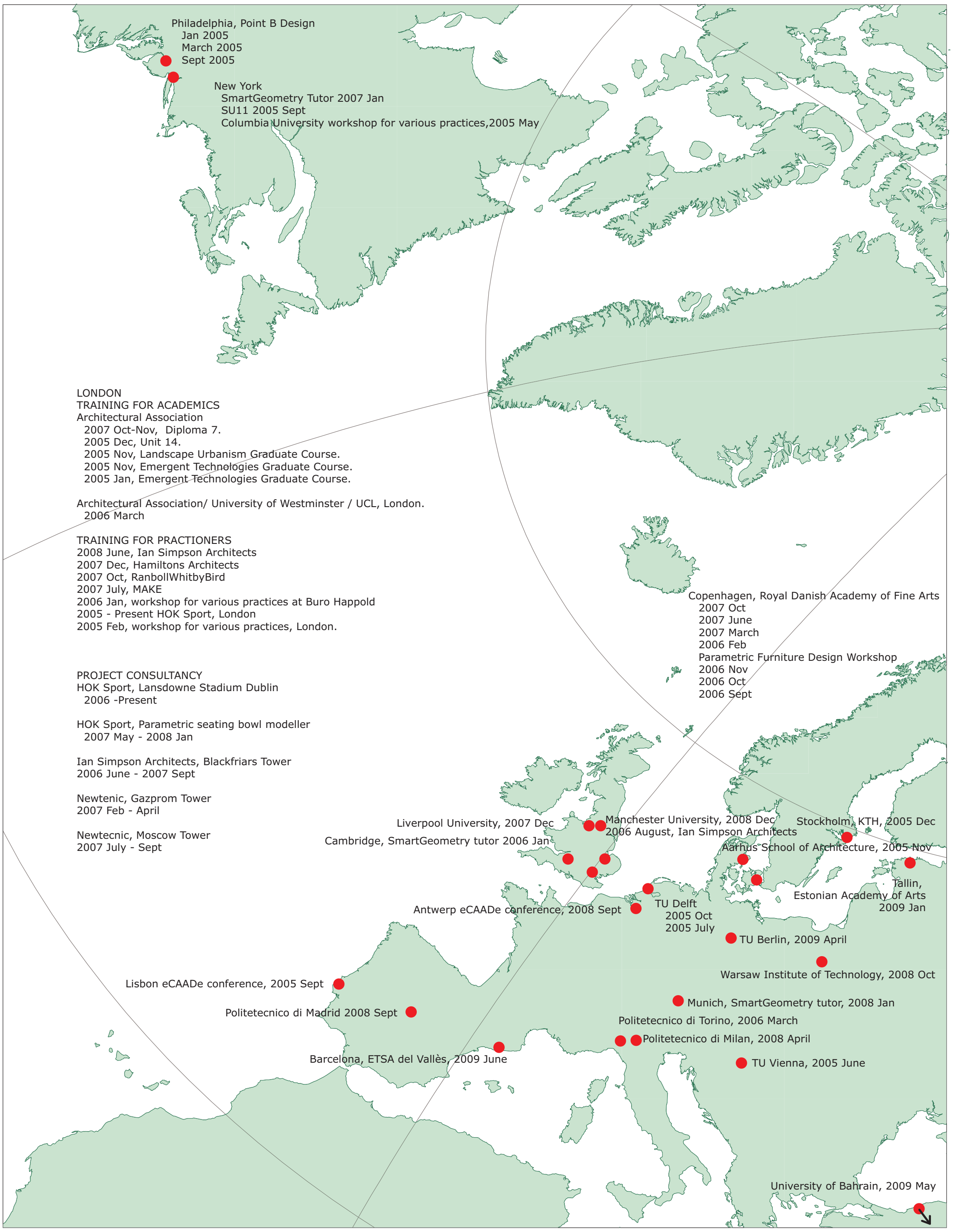

Figure 1.1: Work locations.

artifact is created in order to solve some problem. This definition is expanded by contrasting artificial (or design) sciences (those which are concerned with man-made artifacts) with the natural sciences (those concerned with developing knowledge of natural objects and phenomena).

In architecture, design involves a response to a problem, often the nature of the problem is not clear and therefore the design process also involves developing an understanding of the problem. Lawson (2006) recognises architectural design as “a matter of finding and solving problems”. Subsequently many alternative solutions may exist and design, or finding a solution, becomes a process of selecting amongst them. For Simon (1996) this should be a rational choice, but in architecture choices based on aesthetics may seem irrational to some. Gero describes the design process as one that “involves exploration, exploring what variables might be appropriate” (Gero, 1990).

In summary “design” in this thesis is a task that involves defining a description of a problem, then generating and searching amongst alternatives to find a solution that satisfies the problem. “Parameter” has been defined as any measurable factor that defines a system or determines its limits. “Parametric design” is understood as a process where a description of a problem is created using variables. By changing these variables a range of alternative solutions can be created, then based on some criteria a final solution selected.

On this basis it could be said all design is parametric. For the purposes of this thesis this definition needs expanding to include the context of contemporary architectural practice. Contemporary design practice is dependant on the use of computers. The computer supports parametric design by providing a means of defining a model[1] which represents the design problem. Such a model defines the relationships and parameters in the design problem and by adjusting these parameters alternative designs can be configured.

A parametric model can be defined by programming or writing code using a specific programming language. Alternatively many computer aided design (CAD) applications can be extended to provide parametric functionality by using their application programming interface (API). More recently CAD applications have become available that have parametric functionality that the user can control through a graphical user interface (GUI)[2]. This kind

[1] Model is understood as an abstraction of reality, this is discussed by Holland (2000).

[2] This parallels broader current cultural observations of service orientated applications and the democratisation of programming which has been discussed in the popular press (Economist) making programming simpler through

of application is described as parametric software, typically these applications provide the option to use a scripting[3] language to further customise the parametric functionality. Parametric software offers users the means of creating relationships and associations between geometric objects and objects that are definitions of variables or functions. For this reason parametric design is sometimes referred to as associative design.

Parametric design is therefore understood in this thesis to be the process of developing a computer model or description of a design problem. This representation is based on relationships between objects controlled by variables. Making changes to the variables results in alternative models. Selection of a solution is then based on some criteria which may be related to performance, ease of construction, budget requirements, user needs, aesthetics or a combination of these.

1.3 Aims

The main goal of this thesis is to establish strategies for architectural parametric design. The need for strategy in architectural parametric design is driven by the popularity of parametric methods, and the observation of a new specialist role that deals with implementation of these methods. The potential benefits of parametric design have been acclaimed while simultaneously it is acknowledged that the complexity and time required for design tasks that incorporate parametric methods has increased (Aish & Woodbury, 2005; Woodbury & Marques, 2006). Strategies will assist future generations of architectural designers to overcome these added complexities and understand how to implement the technology to benefit from the opportunities offered.

A strategy is adaptable and involves choice and selection from multiple options. Strategy is not repetition of a previously successful technique but assessment of circumstance and the development of a direction based on rational reaction. In architectural design the problems encountered are complex and vary greatly. The exact same approach is rarely suitable for new design scenarios. This thesis therefore aims to expose strategies and the basis on which they develop rather than specifying explicit methods.

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the use of graphical systems (mash-ups) and Bill Gates recent comments on making the most of subroutines. For example web pages that combine google maps API with data from other websites.

[3]The words ‘scripting’, ‘coding’ and ‘programming’ are interchangeable. They all mean writing lines of computer program or code.

A further aim for this thesis is to link theory of design to architectural practice. Through this process a more detailed understanding of applied parametric design is developed. Examination of theoretical and practical sources identifies key similarities and differences which suggest further directions for study. The theoretical basis is defined through critical review of two literature sources; general theory of design, and theory relating to computational and parametric design. The current state of parametric design in industry is established by analysing published material originating from practice. In assessing the state of practice this thesis contributes a systematic analysis of parametric design activities spanning multiple design offices.

It is acknowledged that the published material from practice may be restricted by the commercial need to maintain a competitive edge and client confidence. The scope of what is reported may therefore be limited. This is balanced by the author undertaking a series of case studies. These studies offer a means of deeper enquiry into areas not described in the practical literature. Generalised observations are made from analysis of this framework of theoretical and practical reviews, based on these, strategic directions can be selected.

1.4 Objectives

In order to develop an understanding of parametric design strategies, a deeper understanding of the choices available to the parametric designer is required. In this thesis it is proposed that a comprehensive understanding of the parametric designer can be gained by examining the **tasks** involved and **considerations** required in a parametric design process. Based on this approach, parametric design strategies will be identified.

Comprehension of tasks and considerations form the key objectives for the thesis. These are developed through a combination of review, analysis and examination of theory and practice. The theoretical basis of this study originates in design methodology and extends to include theory that attempts to deal with parametric tasks. The practical basis is formed using published material from architectural and engineering firms and a series of case studies undertaken by the author. Throughout this document published material from practice is referred to as practical literature, and the case studies undertaken as part of this research are referred to as practical observations.

1.4.1 Tasks

The first step in developing an understanding of the role of the parametric designer in practice is to identify the **tasks** the parametric designer is engaged with. This entails establishing the extent of the parametric design role in contemporary practice. This will require identifying stages of the design process in which the parametric designer participates. The activities undertaken, position within the practice, relationship to the architectural design team and relationship to the construction team will be described. This process will result in a general description of tasks covered by published material. Aspects of professional parametric practice lacking detailed descriptions will indicate areas of interest that the practical observations should focus on. By seeking to develop fuller descriptions of parametric design tasks that have not yet received detailed attention this thesis will contribute to the body of existing literature.

Theoretical descriptions of parametric design tasks will be identified. It is likely that these descriptions will be attempts to formalise tasks that may be implicit in the practical literature. Formal task descriptions from theory will provide deeper insight into tasks described in practical literature. Practical illustrations of formally described tasks will be sought and the validity of theoretic task descriptions tested.

1.4.2 Considerations

Identifying and describing the tasks that the parametric designer is involved with provides initial insight into the role. An astute analysis will be achieved through determination of **considerations** that are taken into account whilst undertaking those tasks. In this thesis a consideration is regarded as something that a parametric designer keeps in mind when making a decision or evaluating facts related to the task they are undertaking. Establishing what these considerations are will indicate influences affecting the approach to a specific task. Developing an understanding of considerations will demonstrate more subtle aspects of the role. Particularly how the decision making process is influenced by the practice, type of project, people involved, stage of design, expected extent of involvement. Considerations will be described in order to understand the way in which the task is approached, which in turn, will influence the chosen strategy. Considerations documented by practitioners will be summarised. Where an account of a task and associated outcome is given it will be possible to establish what considerations were made.

Theoretic descriptions of considerations will be more formal and these will also be identified. The value of theoretical considerations will be assessed using practical observations. Practical observations will be focused on tasks that have not yet received detailed attention in the practical literature. Observing these tasks will provide an opportunity to describe previously undocumented considerations associated to the task under observation.

1.5 Methodology

The key objectives are to develop a comprehensive understanding of the **tasks** and **considerations** related to the role of parametric designer. Based on this, the aim is to identify strategies, the nature of a strategy is first defined. In this section, ways in which these objectives may be addressed are discussed. Three possible research approaches are described; the first is a review and use of literature originating from practice, the second is the use of case studies and thirdly the use of laboratory type experiments with designers. The first two of these approaches are used in this thesis and reasons that justify this choice are described. Issues relating to the chosen approaches are discussed, including reasoning in the choice and number of case studies undertaken. Research involving the use of case studies where the researcher is actively involved with the subject is recognised as participant-observer research. Key issues with this method are noted. Finally a set of precedents where architectural research has been conducted through case studies is presented. The next section then describes the specific means by which the thesis objectives will be achieved using this methodology.

1.5.1 What is a strategy?

Current thinking in the field of strategic planning defines some general principles that are applicable for developing parametric design strategies. Mintzberg (1978) describes how strategies form as the result of two components; deliberate and emergent strategy. Deliberate strategy is that which is pre-planned, whereas emergent strategy is the result of the way an organisation (architectural practice) interacts with the environment (the specific circumstances surrounding the design task). As a result Markides (1997) describes the formation of strategy as requiring continuous reformation and reassessment. These ideas have been reiterated recently by Moncrieff (1999) who described strategy as partially deliberate and partially unplanned.

Mintzberg's definitions of deliberate and emergent strategies provide distinction between strategies proposed in the thesis and what is added to them when they are implemented in practice. The strategies described later in this chapter are considered deliberate strategies, which when implemented in practice are combined with the emergent strategies that occur as a result of the specific situation.

In the context of the strategies proposed in this thesis, emergent strategy operates at two levels. The first (higher) level determines which combination or individual deliberate strategy to apply and indicates what stages of the design process they are applied to. At the lower level emergent strategy determines the sub-tasks and procedures the parametric designer must engage with and how they should address them. It is proposed that the implemented strategy develops on both levels, approaching the design problem by iteratively assessing the situation.

1.5.2 Use of literature from practice

Published material from practice is the result of efforts by practitioners to encapsulate a process after it has been completed. These accounts sometimes reflect on multiple projects. Consequently they offer a concise way of assessing the processes taking place accross a series of contemporary practices. This type of assessment would otherwise be difficult to achieve due to the size of practice and the effort required to distill structured observations from large amounts of information. The size of practices mean that without a personal connection it would be difficult to access the relevant group or person within the practice. A personal visit to a practice is likely to result in documentation of anecdotal experience rather than the succinct information presented in the published accounts.

While the accounts from practice provide valuable insight, they are ultimately the product of a commercial organisation that has to make profit and satisfy stakeholders. Consequently it is likely that the literature will not disclose details that would diminish their competitive position or reputation in the industry. It is reasonable to expect that not all creative skills are described in detail. Additionally it is possible that exploration of fruitless directions, mistakes made and technical limitations are not described. It is therefore important to note that it is anticipated that published work from practice will not provide a full description of all aspects of a parametric design process.

A final consideration when reviewing practical literature is the fact that some practices have more incentive to publish their work than others. This could result in an unbalanced view of the state of practice. Practices that have not published may not wish to share what they have done for the commercial reasons stated above. Alternatively a practice may pursue publicising work as a means to win new work and establish or maintain a reputation in the industry. Practices that have not published may already consider that their reputation and parametric capacity is established and they do not need to publish in order to win more work. For this reason the motivation for publishing work should be considered when reviewing it.

1.5.3 Use of case studies

Observations of specific procedures, first hand, in the context of practice, using case studies, can provide an alternative view of practice not captured in the generalised descriptions published by practitioners. Case studies offer the opportunity to investigate aspects that in the literature may have been over-looked or commercially guarded. Practical observations from case studies can broadly avoid issues relating to protecting commercial interests of practices involved with the study.

Practical literature is written after the event, descriptions will be generalised, rationalised and related to the finished process rather than the development of the process. Case studies will be able to report on events as they happen, capturing information on activities that moved the design forward and activities that led to a dead end of enquiry. Case studies allow the recording of both these valuable information sources that may be overlooked in the practical literature.

While case studies offer a means of addressing areas beyond the scope of the practical literature there is also a need to realise the limitations. Observations are very specific to each practice and project and will not be completely replicable even on a similar project with the same practice. Documentation of new case studies will add to the published case studies and may cover aspects not previously dealt with. In order to gain some meaningful understanding, generalisations need to be made based on analytical reflection.

Practices involved in case studies have been made aware that descriptions of those processes may form part of this thesis. Respect for the practices interests is required, any material considered sensitive has been discussed with the practice and addressed before inclusion in the thesis. Any particular practical observation that a practice feels is detrimental to their commercial position may still be referred to, but without attributing it to a specific project or practice.

A single case study is unlikely to reveal enough aspects of great interest to provide enough material. Several case studies need to be undertaken in order to provide the opportunity to observe enough events of interest. Multiple case studies are also necessary to negotiate the unpredictable nature of architectural practice. At the start of a project it is not possible to know the time span, what precisely the project will involve or what is required. Working on multiple projects will also provide the opportunity to develop good working relationships with practices which will be necessary for successful projects. Good relationships with practices will increase the chances of opportunities to observe further projects. In order to maintain these working relationships it will be necessary to continue to work with the practice even when the work involved is no longer relevant to the thesis.

Use of multiple case studies will generate large quantities of data, material that features in the main body of this thesis will only be included as a result of analysis of the literature from practice and theory. Inclusion of material is justified because it addresses one or more of the objectives described above.

1.5.4 Use of design experiments

Design method can be studied through conducting empirical experiments where groups of designers participate in a hypothetical design scenarios. Lawson (2006) has noted how difficult it is to conduct empirical work on design processes. This is due to the fact that many of the design decisions are internal and the physical outcome may not represent the actual process. Lawson's own experiments involved two groups with different educational backgrounds, scientific and architectural. The groups had to attempt a problem solving task involving coloured blocks and their strategies for solving the problems were recorded. Based on the way they solved the problem their cognitive style was inferred. Attempts to summarise the findings demonstrate how complex influences on the designers studied make forming conclusions difficult.

Eastman (1968) conducted experiments with more experienced designers who were tasked with the redesign of a bathroom. All the conversations and drawings that took place were recorded and analysed. The results indicated a particular approach to problem solving dependant on representation and helped by previous experience. Eastman has similar concerns regarding empirical studies as Lawson. He questions the depth that the observations allow into the problem solving process. His approach is dependant on capturing external expression of the information used in design and he believes some of the design processes may be missed. The use of multiple mixed representations of the problem and solving process are difficult to deal with in the analysis. Eastman also acknowledges the way in which the problem used for the experiments may actually be a part of a larger design. The influence of the larger design therefore does not play a role in the study. The series of design phases that take place in practice between receiving the commission and producing working drawings are not captured in Eastman's study. Despite weaknesses in the research approach Eastman believes it is still possible to gain powerful insights and observe weak techniques which may lead to new design methodologies.

By recording participants' comments in response to a more complex building problem, Akin (1986) hoped to study parts of the design process in isolation. Akin found that it was difficult to pursue his goals as participants behaviour was unexpected. They were constantly generating new goals and redefining constraints simultaneously undertaking the aspects of the design process that he wished to study independently.

1.5.5 Selected approaches

In order to address the aims and objectives of this thesis, a detailed understanding of the role of the parametric designer in practice is required. It is proposed that this is undertaken in two ways; the first is to review published material concerning applied use of parametric design and the second to undertake direct study and participation in practice based case studies. This combined approach will offer a balanced view of the role of the parametric designer. The breadth of the practical literature includes the views of several practices, sometimes describing multiple projects. These concise summaries will provide a broad view of the current state of practice. Conversely the immediate nature of direct observations will provide an opportunity to examine the detail of a process in a specific environment. Use of hypothetical design experiments has not been chosen, as the need to work with real constraints is regarded as important. As noted by Eastman (1968) and Lawson (2006), hypothetical approaches can not emulate the same complexity of a practice based project with multiple players making decisions based on various constraints. Since this thesis is primarily concerned with use of applied parametric methods, hypothetical projects have not been pursued.

1.5.6 Participant-observer research

The proposed case studies involve the author undertaking parametric design tasks acting as a consultant to commercial practices. This position simultaneously allows participation, observation and documentation of the design process. Use of case studies in research where the researcher is actively engaged with the subject being studied is described in research literature as participant-observer. A body of theory exists that formally describes how to undertake this type of research and the following paragraphs set out some salient points extracted from this literature.

Generally the participant observer process is acknowledged as one where theory emerges from study within a context (Fook, 2002). In order for this to happen, the researcher must be in the setting where the study takes place (Maykut & Morehouse, 1994). The researcher is required to socially interact with members of the organisation being studied (McCall & Simmons, 1969). Maykut & Morehouse (1994) also note that for a theory to emerge, the process should begin with a broad focus. During the research period the focus becomes more specific based on analysis of observations and records. Key methods available to researchers in this field are, direct observation, direct participation, interviews and document analysis.

Participant-observer is criticised due to difficulties in control and measurement which make generalisation and predictions difficult (Fook, 2002). The specific nature of the object of study means that the results are very hard to replicate (Jarvis, 1999). In this thesis it is intended that the specific nature of the case studies will be balanced by undertaking a broader view of the use of parametric design in architecture through reviewing published material. The reviewed literature forms an initial framework which becomes broader and more substantial once findings from the case studies are inserted. The participant-observer approach to research offers a means of gathering knowledge in the form of, tacit knowledge, knowledge of experience and working or practical knowledge. This type of knowledge cannot be acquired from literature review alone. As this thesis is concerned with developing understanding of an applied practical role, these forms of information are of great value.

1.5.7 Case study based research in architecture

Several precedents for the development of architectural theory based on some form of participant observation research exist. The participant-observation approach falls into a broader branch of research method called ethnography. Research into reusable patterns for parametric design undertaken by a group of researchers headed by Woodbury (2008) and published by Qian *et al.* (2007) is described as ethnographic. These studies are based around the observation of participants working individually at training events such as SmartGeometry workshops (SmartGeometry, 2008). The results of this study have been used to develop a reusable library of “patterns” or code for helping designers learn about parametric design. The study takes place outside the design office environment and is focused on individuals’ learning capacity while undertaking actual design tasks.

The Royal Melbourne Institute of Technology (RMIT), Spatial Information Architecture Laboratory’s (SIAL), Embedded Research group aims to develop a better understanding of architecural practice using enthnographic methods in the work place SIAL (2006). The program intends to capture research in practice that is lost because it is not documented. Based on this the aim is to advance knowledge and approaches to design. Here researchers are based in practice and their research is project-based. Broadly their goals are to develop new areas of research and development that will maintain the competitive position of Australian architectural and engineering design and its role in the construction industry in the world market.

Two recent publications from the Embedded Research program are a thesis by Nicholas (2008) and a paper by Hyde (2007). In his thesis Nicholas explores the ways in which three-dimensional digital environments facilitate closer links between architects and engineers. The basis of this thesis were eight case studies, which were primarily design investigations, undertaken during a two year working period with ARUP Australia. Hyde explored the way in which emerging technology can assist smaller practices to compete with larger architectural firms, this too was undertaken with a series of design studies.

Several books have been developed as a result of research efforts where the focus has been the study of architectural practice. In "Design Thinking", Rowe (1987) examines the internal logic of decision making in architectural design processes through observation of a series of architectural projects and develops some theoretical considerations. In a similar way Lawson (1994, 2006) uses a series of observations of designers to study the psychology of the designer in order to gain insight into the process of design. In "Architecture: The Story of Practice", Cuff (1991) spent several years working with and observing individuals and architectural practices in the United States. The outcome of this study was an understanding of the social aspects of how design problems are explained and solved. A similar study by Krauss & Myer (1970) focused on a team of architects in Boston over an eighteen month period. This study followed a single project from concept to preparation of construction documentation. They documented the design stages and the decision making that took place.

Akin (1986) describes how these empirical studies have proceeded first with observation and recording. Then a paradigm that can predict the observed is hypothesised. Next the validity of the hypothesis is tested with further empirical studies.

Various academics have called for a stronger link between research and practice, Kvan (2004) suggested benefits in strengthening links between research and practice in computer aided design. Martens *et al.* (2007) recommend that architects need to engage with software and emphasise the importance of research in computers and design.

1.6 Methodology applied to objectives

1.6.1 Tasks

Summary of **task** objectives:

- Identify task descriptions that have been defined by theorists.
  - Illustrate these with examples that have been described by practitioners.
  - Observe tasks that have been described by practitioners in case studies.
- Use extent of tasks that have been described by practitioners to guide focus of practical observations.
- Definition of activities parametric practitioners are involved with.
- Description of the position of the parametric practitioner in practice.
- Description of parametric practitioners relationship to design team.
- Description of parametric practitioner relationship to construction team.

The first step in defining a description of the tasks of a parametric designer is to analyse theoretic literature to identify a set formal definitions. This will define a set of goals for further chapters. Evidence of this task is sought in the review and analysis of practical published material. If the evidence exists it validates the theoretical description. If no evidence of the task exists it then defines a focus for the case studies. If it is possible to directly observe this task as part of a case study the theoretic description is validated. If it is not possible to observe the task the theoretic description will be considered invalid. It may also be possible that partial evidence in the practical literature exists or a similar task is observed in the case studies. Partial evidence would suggest the description identified in the literature requires slight modification for it to define a task. Partial evidence is recorded and the required modifications discussed. This process will establish if tasks described in theory are valid in an applied situation.

Parametric design task descriptions and an understanding of the extent of the role will be developed through detailed analysis of practical publications. Through examination of the literature activities in parametric design, tasks will be defined. Analysis of task descriptions will identify the stages of the design process where parametric processes were applied. Review of the practical literature will provide descriptions of the position of the parametric designer in practice, their relationship to the design team within the practice and the broader construction team beyond the practice.

The task descriptions developed through analysis of literature will indicate tasks and activities that lack a full description. The focus of practical observations will be devised to actively seek and observe areas that have not been fully documented. In this way the new case studies will add to the published descriptions of tasks related to the parametric designer. Tasks that have not been identified in the literature but observed in practical observations will be identified and described.

1.6.2 Considerations

Summary of **consideration** objectives:

- Identify considerations described by theorists.
- Assess the validity of theoretic considerations using practical observations.
- Use extent of consideration descriptions by practitioners to guide focus of practical observations.
- Identify considerations that have been described by practitioners.
- Derive considerations based on descriptions of task, related approach and implications.

Analysis of theoretical literature will reveal formal descriptions of considerations. If these have been documented in the practical literature, a practical example will be developed. If these theoretic considerations have not been described by practitioners, practical observations will be used to assess their value in an applied situation.

Analysis of practical literature will identify documented considerations that have been made by practitioners as they undertake parametric tasks. Where considerations in the practical literature are not explicitly stated it will be possible to extract a consideration through analysis of a specific task, approach taken and the implications of the action. The circumstances under which the task was carried out will add further understanding to the considerations made.

Analysis of practical literature will indicate specific areas of parametric design which the practical observations should focus on. These will involve considerations that have not received detailed description in the literature. By focusing on these considerations and analysing documentation and observations from new case studies further considerations will be identified.

1.7 Thesis structure (Outline of chapters)

The following chapter establishes a broad background in design theory. Building on this, chapter three develops the theoretical basis to include publications that are focused specifically on parametric design. Chapter four identifies the current state of practice as revealed in published material from commercial firms. The first of the case studies, Lansdowne Road Stadium involved geometric definition and development of facade design. This is presented and reviewed in chapter five. Chapter six describes and analyses the second case study, the Seating Bowl Modeller. This is concerned with developing a reusable tool for the design of spectator facilities at sports venues. Several further case studies were undertaken in the course of this research. Chapter seven briefly reviews those studies that also make a significant contribution to the thesis. Chapter eight concludes the thesis with a review and analysis of the findings of the research. This also presents to the identification and descriptions of strategic approaches to parametric design.

Chapter 2

Design theory background

2.1 Introduction

This chapter aims to establish a broad theoretical basis of design theory, based on a review of a series of key publications. The following chapter, a review of theory relating specifically parametric design, builds on this foundation.

This chapter presents a view of architectural design as a problem solving process. Two general problem solving methods are described and the classification of design problems is discussed. Architectural problems are often regarded as belonging to a category of problems which are difficult or impossible to fully describe at the start of the design process. The complex nature of architectural problems means that initiating the design process is dependant on the designer's experience and ability to select and impose some structure on the problem. This initial trajectory establishes a set of boundaries or constraints within which a design solution may lie. By selecting and evaluating designs from this space, the designer begins to build a more detailed understanding of the problem. By breaking the problem into parts and by using suitable representation methods the task can be made more manageable.

2.2 Problem solving methods

Polya (2004) described four general principles for problem solving; understand the problem, devise a plan, carry out the plan and look back or review. While these were intended for mathematical problems, the general nature of the principles means they are applicable to design problems. The first principle, understand the problem, involves restating the problem in terms that are understood by the problem solver. This may involve drawing on some form of imagery to visualise the problem. The amount of available information is assessed to ensure there is enough to develop a solution. Polya suggests that the next principle, devising a plan, becomes easier with experience. He proposes several strategies that can be used to construct a plan including eliminate possibilities, consider special cases, look for a pattern, solve an equation, use a formula, use a model and solve a simpler similar problem. The third principle, implementing the plan is regarded as easier than designing it. The chosen plan should be pursued until it is clear that it will not yield results. It should then be discarded and an alternative plan selected. In his final principle Polya suggests the problem solver should reflect on both successful and unsuccessful plans in order improve their problem solving abilities.

A similar fundamental process is described by Newell *et al.* (1957). They regard the process of problem solving as moving from a “task environment” (the context or situation within which the problem exists) inward to a problem space. Within this space, problem solving takes place as a search. Methods define the way in which the search is undertaken. These methods are organised by a production system, which is controlled by the human mind. Newell *et al.* describe the mind as an information processing system, their model of problem solving is based on information processing theory. They propose three general search methods; recognition of solutions, generate-test and heuristic search. Recognition is about knowing the answer, usually this happens in later design stages when the size of problem space has been reduced. The generate-test method involves production of solution candidates which are tested to see if they comply with the requirements of the problem. Therefore the generate-test method works only in cases where the requirements are known. If the problem space is large then heuristic search is applied. This method makes use of information already obtained (through experience) to guide the search in steps that reduce the number of alternatives. Once the heuristic method has reduced the range of possibilities, a solution can be found by the generate-test or recognition methods.

2.3 Architectural design problems

Lawson (2006) has claimed that often in architectural design the problem cannot be comprehensively stated at the outset of the process. The difficulty in describing architectural problems means that there is potentially an infinite set of possible solutions. Architectural design solutions are a result of negotiation between problem description and solution. Lawson's chronological review of architectural design models leads to description of a generalised, iterative, three stage model of the architectural design process. This consists of analysis, synthesis and evaluation. This model attempts to accommodate the need to negotiate between problem and solution. In his study of designers in practice, Lawson (1994) observes that, in architecture, the ability to select the right problem to solve is necessary for success. Lawson's study also indicates that the design task for an architect is about both identifying problems and solving them.

In "Reflection In Action" (Schon, 1991) the duality of problem stating and solving in professional practice is also discussed. Schon claims, "Professional practice has as much to do with finding the problem as with solving the problem found". Wade (1977) describes this as a circularity between problem and solution. This is demonstrated by Wade in his observation of the way in which the seeds for the solution are contained within a problem statement. Similarly Heath (1984) summarises the reciprocal nature of understanding problems and defining solutions as "a problem well stated is a problem solved".

Simon (1975) claims all design problems are solved by searching a large space of possibilities. These spaces are referred to as solution or problem spaces and these exist within the task environment or context. Heath (1984) notes how the task environment for architectural problems is generally complex, therefore the size of the solution space tends to be immense. Subsequently architectural problems are often classed as ill-structured. Rowe (1987) describes ill-structured problems as having neither goals nor means clearly defined at the outset. For this type of problem effort is required to clarify, define and redefine the problem. This class of problems can be defined in contrast to well defined problems. In "The Structure of Ill Structured Problems" Simon (1973) describes how an ill-structured problem can be identified by considering the typical characteristics of well-structured problems, which are;

- A clear means for testing proposals exists.

- There is at least one problem space within which a representation of the problem state and goals exist.
- Changes from the initial state to new states can be represented.
- Knowledge gained can be acquired and represented within one of the problem spaces.

A further class of problem is discussed by Rittel & Webber (1973) from the perspective of urban design. “Wicked” problems describe those with requirements that are incomplete, contradictory and changing. Rittel and Webber define this type of problem as having no definitive formulation, there are no rules that define the point at which the design process should stop. This is imposed by time and cost constraints. There is no obvious testing procedure for the solutions. Solutions to these kinds of problem can be described as good or bad, but not true or false. Rittel and Webber believe that urban design will generate waves of consequences, its success can only be measured once these have dissipated. Each attempt at a built urban solution has significant impact and it is therefore hard to treat it as a trial and error process as with mathematical solutions. Each problem is considered unique and therefore previous solutions can only indicate possible solutions. Solutions to parts of such problems can reveal or suggest other, more complex problems.

Jones (1992) observes two design methods in practice; blackbox and glassbox. These are a direct result of the problem type. The blackbox approach is present in wicked, ill-defined design problems and solutions seem to appear from within the designer’s mind. The glassbox approach is observed when the design problem can be explicitly described (is well-defined) and the solution understood in terms of the problem. The glassbox approach involves a planned sequence of rational steps. This is contrasted with the blackbox approach where all of the design process is internal to the designer and not open to rational or empirical discussion. Jones regards architectural design as difficult because designers are obliged to use current information to predict a future state that will not come about unless their predictions are correct.

2.4 Origins of design ideas

In “Notes on the Synthesis of Form”, Alexander (1964) describes a means for mapping out design problems. This involves listing all requirements of a design and then looking for interactions between them. Each interaction is labelled positive, negative or neutral depending on whether they complement, inhibit or have no effect on each other. In this way a diagram of forces is established. This description is passed into a computer program that processes and breaks the problem into simpler sub problems. Subsequently this proposal for tackling design problems has been criticised by Alexander himself (Alexander, 1992) and also by Broadbent (1973). The primary criticism relates to the need to list all the requirements at the outset. This has been shown to be difficult or even impossible for architectural problems. The secondary criticism is that the strengths of interconnections between requirements will not be equal strength and they will also be hard to define.

Jones (1992) acknowledges that what is known at the outset of a design process might be little, and therefore a difficulty in starting the process may arise. He proposes a model in three parts; divergence, transformation and convergence. This directly deals with the production of ideas. First the designer actively diverges from what exists in terms of a problem description. By doing so objectives and problem boundaries are discovered. The design brief can be refined using this new understanding of the problem. Next, the transformation stage seeks to impose patterns on the divergent search results. This involves splitting the problem into sub-tasks and identification of constraints related to each of these. Each set of sub-tasks represents an alternative structure to impose on the problem. Lastly, the convergence step involves reducing the range of options generated by the previous into a set of rational options and selecting one from these.

Rowe (1987) conducted a series of practice based case studies in an attempt to discover an internal logic in architectural and design decision making. One simple observation, based on his studies, is that designers often use analogy to initiate design processes. Rowe found that the analogy was often based on a previous experience or a method applied in tackling a similar problem. He observed that the analogy allowed the design process to start by instigating a series of episodes which defined a series of smaller problems. Rowe found that the way in which designers organised and structured the problem space had a great influence on the design direction. He also noticed that architects had a tendency to become attached to their initial ideas.

The need to pre-structure a design problem is reflected in the design model proposed by Hillier *et al.* (1972) called “conjecture - analysis”. This model involves defining a speculative theory which pre-structures the problem. This is then analysed to check it can be used to develop designs that conform to the design requirements. The conjecture for the design and the problem specification therefore proceed in parallel.

Darke (1978) proposed a means for idea generation used by architects called the “primary generator”. She adds this as a starting phase to the existing model proposed by Hillier *et al.*. Darke’s “primary generator” originates from her studies of the design processes for a series of residential buildings. Her observations show designers relying on subjectivity and not rational analysis of the design problem. The “primary generator” is not a list of all constraints but a way to start the problem based on the a group of concepts such as expressing the nature of the site, maintaining social patterns and other general values. This informs the conjecture which can be tested against the design requirements. Darke describes the effect this has on the number of possible solutions as “variety reduction”.

Like the divergence, transformation and convergence sequence proposed by Jones, Darke’s method involves proposing an idea based on an original understanding or visceral notion of the problem and then examining it to see what it suggests about the problem. Whatever is suggested is then used to inform further studies. This allows the designer to quickly reduce the size of the range of possible solutions by selecting a relatively trivial “primary generator”. This is described as structuring an unstructured field. Lawson (1994, 2006) refers to this type of process as the designer’s central idea or guiding principle. As a result of his studies of practice, Lawson describes these approaches as imposing constraints on the problem, which narrow the range of possibilities. An approach where a particular design idea is considered valid until proven false is also discussed by Brawne (1992) in relation to the work of Karl Popper.

Heuristics is a term that broadly describes these approaches. Heuristic methods are defined as educational and solution seeking approaches which rely on experience and rules of thumb rather than theory. In “Design Thinking” Rowe (1987) describes heuristic design processes as methods for tackling problems based on previous experiences or rules of thumb. A selected heuristic defines a set of constraints which determines how the design is tested and evaluated. The constraints define or organise an initial problem space structure. The choice of heuristic therefore influences the later design directions. Schon (1991) suggests designers should analyse these tacit processes to produce a "Frame Analysis" which is a repertoire or case library of strategies to choose from. Newell *et al.* (1957) define heuristic as "any principle, procedure or other device that contributes to the reduction in the search for a satisfactory solution".

2.5 Problem spaces

Internal sources can define an initial set of constraints. Lawson (2006) describes how a model of design can develop through gaining further understanding of other constraints which relate to requirements and desirable relationships in a design. Lawson proposes that an understanding of these can emerge from an iterative model of analysis, synthesis and evaluation. This model was later superseded by the "conjecture-analysis" model (Hillier *et al.*, 1972) (described above) as it was thought to be inadequate in instigating the design process. Lawson's model of design is a problem space (figure 2.1). The constraints of a problem define the boundary of the problem space. Design problems are typically defined by multiple aspects and the problem space itself is therefore multi-dimensional. Rowe (1987) defines problem spaces as "an abstract domain containing elements that represent knowledge states, some of which are the solution states to the problem at hand".

Heath (1984) describes the problem space as the problem solver's internal representation of the task environment. He suggests that design methods in architecture should be concerned with the construction of problem space. The designer's task is to manipulate the definitions of this space by imposing structure on the description of the problem. This reduces the size of the space and allows a solution to be identified. Heath makes an important distinction between puzzle and architectural problem spaces. Puzzle problem spaces are well defined, the goals and parts are known, a solution could be found by trial and error. Whereas architectural problem spaces are ill defined, they involve uncertainty in terms of the problem being tackled and the means or components with which to solve it. Heath suggests that methods for dealing with architectural problem spaces allow for constraint relaxation and backtracking to previous solutions.

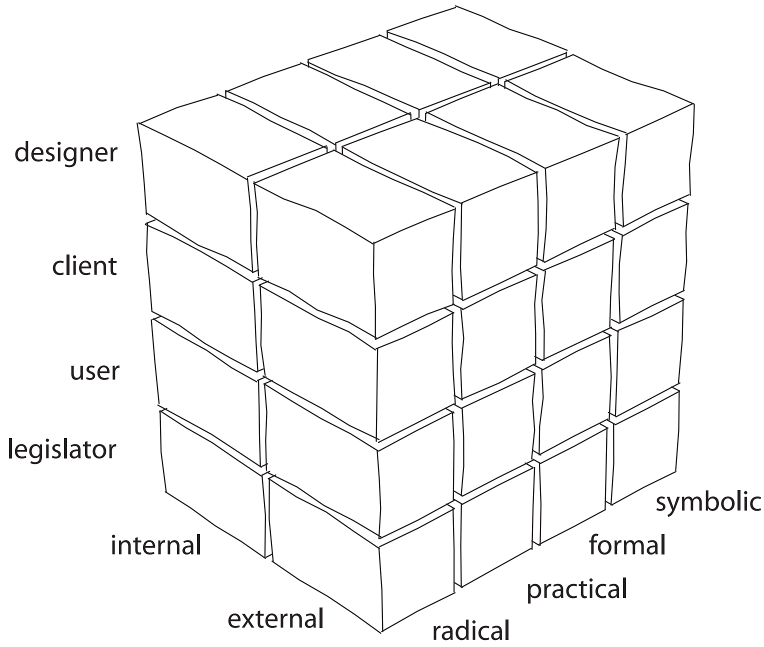


Figure 2.1: Lawson's model of design.(Diagram recreated by author from Lawson (2006))

Newell *et al.* (1957) and Simon (1996) have described how solutions to problems are found by searching in a problem space. States or positions within the space represent solutions include the starting state. A search is conducted by means of operators that allow change from one state to another. Choice of which operator to apply is determined by the problem solver's knowledge. Newell *et al.* describe solving problems not as a random search in space. The space is a frame within which the designer brings knowledge to bear on the search, with enough knowledge the need to search may be minimised. Two searches are occurring simultaneously, search in the problem space and search for knowledge in memory which will guide the search.

2.6 Alternatives and exploration

Simon (1996) hypothesises that the logic of design is concerned with finding alternatives and making a rational choice between them. Observations made by Lawson (1994) in his study of leading architectural practitioners provides empirical evidence to support this. Many of the designers studied expressed a need to generate and assess alternative design ideas. Each assessment involved subjective interpretation that either resulted in further understanding of the design problem or suggested a new direction. Later stages were then influenced by each alternative. Lawson's subjects also demonstrated how the need for alternatives was often maintained until just before project deadlines where last minute changes would be made. Lawson's studies also indicated a need not only for alternatives but also to develop sets of them based on two or more "parallel lines of thought".

Schon (1991) believes that professionals can develop an understanding of a design problem using a series of small scale mental experiments which allow the rapid generation and testing of alternative design ideas. Jones (1992) observed a similar iterative process amongst designers tackling ill structured problems. The series of unstructured tasks within the designer's mind were observed to be coupled with an internal feedback mechanism, based on the outcome of each previous cycle, and a series of design alternatives would be generated.

The way in which architects often initiate a design process has been described as heuristic (see section 2.4. Simon (1996) summarises the role of heuristics in design as a means of finding solutions that are good enough or "satisfice". To satisfice is to find a local optimum, and a design process where seeking of global optima is the goal may prevent finding a good-enough solution. The satisficing process described by Simon is similar to practical observations made by Lawson (2006). Lawson sees solutions to architectural problems as sub-optimal as they attempt to satisfy all constraints, not optimise individual criteria. This is because architectural design solutions need to be both holistic and integrated in complex circumstances.

In "Style in Design", Simon (1975) describes the process of satisficing as a design method where one or more mechanisms for generating design ideas are established together with a series of tests. A set of constraints are identified, these enable satisfactory solutions to be determined. Elements are then generated for consideration as components in the design. Once an idea is generated it is first tested to see if it satisfies some of the constraints. If it does it is added to the design. The second test checks if design progress is being made and which of the constraints remain unsatisfied. This then informs the next iteration where more constraints are added or removed. Simon describes this as a computer program, but he also acknowledges that such a program may exist in the head of the designer. Simon believes that style can be determined by the choice of mechanism used to generate designs.

2.7 Fragmentation of design problems

Rowe (1987) observes that designers often use some form of analogy to start a design process. This triggers a process that he describes as episodic or fragmented. Rowe regards this as the nature of design in practice. Each episode involves the study of a particular design aspect that was typically a part of the complete design problem. Rowe found that these fragments were structured around the generate-test and heuristic methods described by Newell *et al.* (1957). Lawson (1994) found similar traits in designers in his studies of architectural practice. In these studies, he observes that problems are broken into more manageable pieces. The splitting of design problems is justified by Jones (1992) who believes that more intelligence can be applied to smaller problems.

Simon (1973) describes the unstructured nature of architectural design problems. He believes that problem structure can develop through continual modification of the problem space. Simon suggests that problem space modification occurs when new constraints are introduced by recalling previous experiences from long term memory following a prompt from the design process. This would occur when the design is decomposed into problems of component design. The hierarchical structure of design discussed by Simon (1996) originates from his experiments in human problem solving where the limitations of human cognition are observed to reduce when information was broken down into smaller chunks. Solutions to design problems are considered by Simon to be an assembly of components or sub-assemblies and methods of design applied at any level.

Simon identifies two difficulties with decomposition in design problems; interrelations amongst sub-problems and the order which these problems are tackled. Relationships between sub-problems could be complex and that through decomposition this complexity could be overlooked. To avoid this Simon recommends that problems are decomposed into self-contained parts. The order in which these tasks are tackled will effect the final design. Alternative methods of decomposition can be generated and tested according to requirements and constraints of problem. Simon observes that the same process is necessary for musical composition, developing programming code and building design. In "Style in Design" Simon (1975) suggests that the way in which a designer incorporates prefabricated solutions to sub-problems is an expression of style as well as a way of reducing the design search space.

2.8 Representation in design problem solving tasks

Using the example of a simple map, Holland (2000) describes the principle of modelling or representation (figure 2.2). The map represents towns as dots and roads linking them as lines. It retains the essential information about getting from one town to another but omits the unnecessary detail of the mapped landscape. The modelling process is described as: "First we select the details or features to be represented, then construct the model so that some part of the model corresponds to each selected detail." The model concentrates on describing chosen aspects of the world, while disregarding insignificant details. Holland suggests that given a thoughtfully constructed model, new possibilities may be revealed and it can be used for planning and prediction.

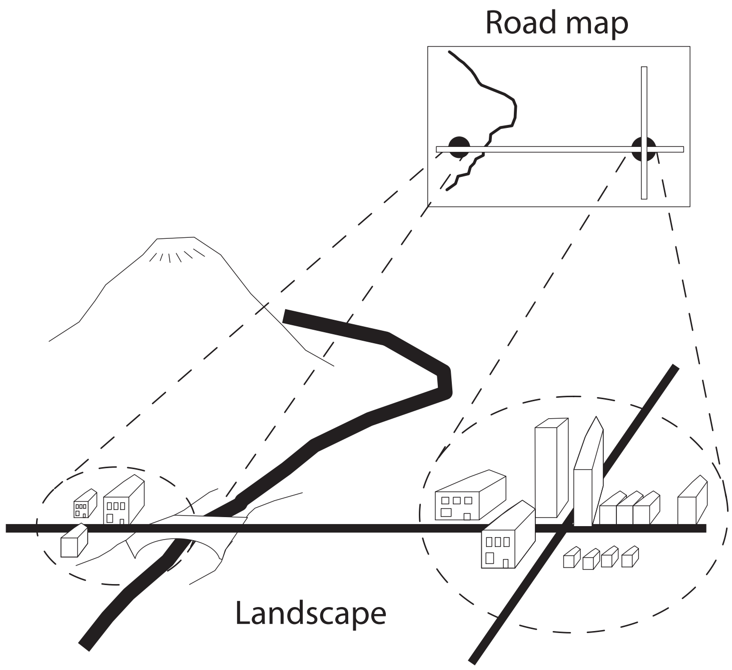


Figure 2.2: Road map as a model. (Diagram recreated by author from Holland (2000))

Lawson (2006) describes a problem space as a "model" of design. His sketch of it shows a three-dimensional stack of cubes with a range of different constraints (figure 2.1), that are annotated along three axes. This is his representation of his description of the problem space. Different points within this model represent the weightings of constraints for a particular problem or for a particular designer. Lawson suggests this may be useful when commencing a design process.

Decision trees are another way of representing the problem space (Rowe, 1987) (figure 2.3). This diagram describes a branching structure where nodes represent decision points and the branches between them the course of action associated with the node. A particular problem solving approach or decision sequence is represented as a sequence of nodes and links. Rowe describes this as an extensive representation and suggests that even ordinary tasks may in fact be complex problems that require a stepwise progression. Rather than representing choices in the diagram Alexander (1964) suggested that nodes could represent design function and arcs between them represent relationships and their strengths.

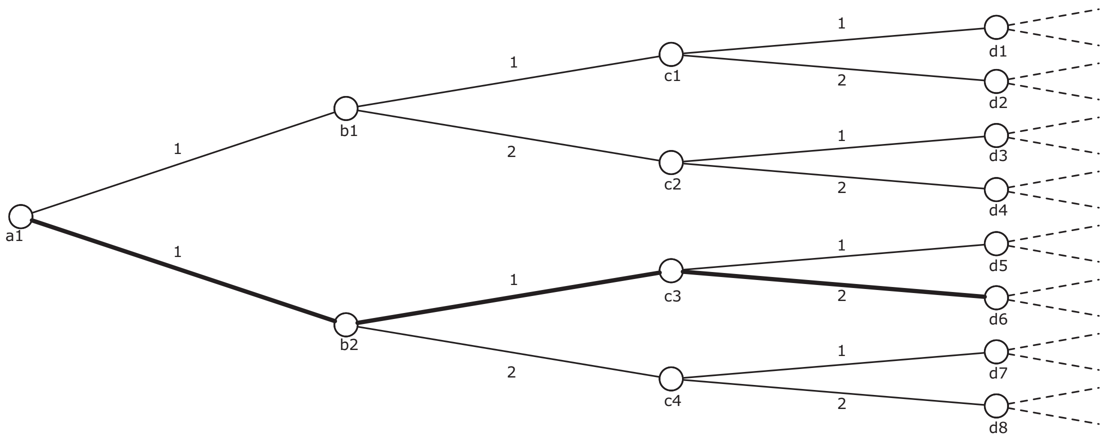


Figure 2.3: Decision tree. (Diagram recreated by author from Holland (2000))

Simon (1996) describes how consideration of representation in design problem solving is crucial. Change between forms of representation is described as fundamental to the process of problem solving. Simon believes that this makes solutions more transparent by forcing the designer to describe the problem or parts of it in a different form. He proposes that the change from Arabic to Roman numeric representation made arithmetic tasks easier. The problem solving programs that Simon describes first require some representation of the problem before they can apply effort to solve it. Developing the representation is concerned with extracting from a written or verbal statement, a description that the program understands. This is considered as equivalent to the process that occurs when a human approaches a problem. Some previous knowledge may be required to interpret the written description.

Simon proposes an outline taxonomy of representation beginning with verbal or written descriptions which can sometimes have a mathematical equivalent. He suggests that if a problem is physical then it can be represented with drawings or models, whereas if the problem concerns actions then it can be represented with flow charts and programs.

Rowe (1987) observes the early use of computer modelling in planning design processes. This was concerned with mapping relationships between humans and the environment. These early modelling processes involved gathering empirical data, such as human movement patterns, and using this as a basis for architectural design. Rowe outlines a conceptual framework for constructing models. The process starts with the existence of an object or situation that is of interest. Next, characteristics or intentions of the situation are chosen. These are questions that the model seeks to answer, which determine the relevant variables and any preceding conditions. Next the chosen situation is observed and abstractions are made, this enables the object in question to be observed in relationship to the selected variables. The abstractions and observations are then translated into a framework that organises factual information. The last stage, according to Rowe, is calibration which concerns testing and making conclusions between the model and the reality represented.

2.9 Summary

The intention of this chapter is to establish an appropriate basis of design theory onto which the following chapter can build. The reviewed literature demonstrates how architectural design problems can be regarded as problem solving tasks provided the nature of the architectural problems is understood. The reviewed literature provides theoretical descriptions and supporting practical observations which support this view of architectural problems. A problem solving task involves developing a description of the problem and then applying some process or method in order to develop solutions. Architectural problems are considered to be ill-defined and develop by reciprocating between problem description and solutions. The problem description defines a multi-dimensional problem space, within which the designer is concerned with searching for solutions. This is undertaken by generating alternatives which are tested against requirements defined by the problem description. The design task is tackled by considering how to fragment and represent the problem. Both of these tasks can reveal new aspects of the problem make it more manageable.

2.9.1 Architectural design as a problem solving task

This chapter proposes that architectural design can be approached as a specific type of problem solving task, provided the nature of architectural problems are understood. The generic models for problem solving proposed by Polya (2004) and Newell *et al.* (1957) illustrate a problem solving process where the first step is about developing an understanding of the problem. Given a problem description, some plan or method is applied in order to find possible solutions. Both models emphasise the role of experience or heuristics in the process. While these models propose logical sequences for solving problems they are not specifically aimed at architectural design problems.

Architectural problems are considered as ill-structured or “wicked” problems. This means that at the outset of the task the goals are unclear and the means by which they will be achieved uncertain. This generates a need for reciprocity between the description of the problem and potential solutions in order to progress the design.

2.9.2 Structuring of architectural problem spaces

To begin to tackle a problem solving task some structure is required, this defines goals and means of achieving them. Once an idea of a goal and the means of achieving it are established, a solution can be produced and evaluated. The results of the evaluation can be used to direct the formation of the next solution or to adjust the initial imposed problem structure. Observations in the literature show that in architectural problems in practice, an initial structure was imposed. This is often based on previous experience and at times was almost arbitrary. This is thought to be the result of the difficulty in describing architectural problems. The designer seeks a way of structuring the problem in order to start the design process. Once a structure is proposed it can be tested or examined for appropriateness in the context of the problem. Based on this test the problem description can be redefined or inform further solution proposals.

The observations of this designer behaviour made in the literature demonstrates the duality between problems and solutions in architectural design. The process also illustrates the way in which experience or heuristics can reduce the range of possible solutions by imposing a structure on the design problem. The imposed structure defines multiple criteria which defines a multi-dimensional problem space. It is proposed that constructing a parametric model can be used to assemble and test imposed problem structures. The initial structuring of the problem informs the way that the model is constructed and this structures the problem space. The ability to adjust the parameters in this model allow solutions to be produced and be assessed by the designer to see if the chosen structure is appropriate for the problem.

2.9.3 Exploring, fragmenting and representing problem spaces

Finding a solution in problem solving activities is seen as a search or exploration of the problem space. It is observed that the search process is organised by designer knowledge. The search process generates alternatives and one of these is selected based on rational choice. The process of generating alternative designs in architectural practice is observed to take place internally, within the mind of the designer, and externally, in the form of drawings and models expressing different approaches. Internal processing reflects the complexity of architectural design tasks and suggests an inefficient and opaque process controlled by a single mind. Parametric design requires the problem to be externalised and connections can be created in a more dynamic way than traditional architectural methods. This would allow further exploration in a transparent fashion.

Fragmentation of design tasks involves breaking the task into smaller more manageable pieces. This has been described as a way in which problem solving can become easier. Breaking a task into chunks can also provide a better understanding of the problem description. Practical observations of architects confirm this occurs in practice and it can be beneficial, provided designers are aware of the interrelations between sub-tasks and the way in which the order of recombination of sub-tasks can affect the final solution.

The principle of representation can be considered as a mapping task where the details of importance are represented and insignificant details are ignored. In an architectural context this occurs in extracting from a brief terms more readily understood by the designer or translating design intent expressed verbally into parametric models. Shifting between representations can reveal undiscovered aspects of a problem which can help develop a solution.

Architectural design tasks have elements that can be represented using all of the methods in Simon's taxonomy: mathematical, spatial and procedural. Parametric design tools offer the ability to develop representations of design problems using all these methods in combination and independently. The ability to use multiple representations in architectural design tasks has the potential to make the process more efficient and lead to the discovery of better solutions.

Rowe's observations on the process of making models or representations are highly abstract but provide a theoretical basis for approaching parametric model making. Given practical evidence Rowe's observations potentially offer a starting point for understanding the process of parametric modelling. Theory relating specifically to parametric model making is reviewed in the following chapter.

Chapter 3

Design theory specifics

3.1 Introduction

The intention of this chapter is to review and analyse theoretic literature in order to address the objective of establishing descriptions of parametric tasks and considerations. This bipartite is proposed in this thesis as a means of developing an understanding of parametric design. This chapter therefore aims to identify existing literature that supports and adds detail to this proposal.

The descriptions of tasks and considerations identified in this chapter are used to focus the review and analysis of published practical material and organise the case studies. For example a task that is described in the literature reviewed in this chapter defines a goal for later chapters. In "State of practice" practical evidence of this task will be sought in published material from practice. The chapters dealing with case studies undertaken by the author seek further evidence to support the task identified in this chapter.

In the previous chapter a series of fundamental theoretical design concepts were established. The theoretical literature reviewed here builds on that foundation. The framework described in the previous chapter demonstrated a view of the design process that begins with an idea from previous experience which defines a space of possible design solutions. In order to explore this space alternative designs are generated by fragmenting the idea into parts and developing representations of these. Solutions are then assessed and changes made to the structure of the problem or the design itself. A series of design models were discussed and contrasted with a current commercial model of architectural design. Woodbury & Burrow (2003, 2006) justify the broad notion that design is a process of exploration of a solution space. This idea corresponds with observed designer action, it is an effective basis for computer support in that computers can amplify designer skills, represent goals, problem spaces and search for designs.

The chapter is structured around the bipartite; tasks and considerations. This two part system was proposed in the first chapter as a means for understanding parametric design. First the tasks identified in the literature are described. Two general categories of task are identified; creating the model and then using this to explore the design space that it defines. Descriptions of the model creation process involve developing a problem description and externalising ideas (actually constructing a model). The task of design space exploration involves finding appropriate parameters, generating alternatives and assessing these alternatives. This hierarchical description of parametric tasks is then used to structure the next section; considerations. In this section the considerations that the parametric designer should make when undertaking these tasks are identified.

Lastly the findings of this analytical review are summarised. This summary defines the tasks and considerations that the next chapter seeks to identify in the practical literature.

3.2 Tasks

The model is a representation of the design problem. The structure of the problem can be described in terms of the functions, requirements and constraints, therefore these need to be identified and expressed. Once the problem structure, or part of it, has been identified, a specific tool or software can be used to construct the model. This involves developing the relationships between geometric elements and part of this process involves breaking the problem into sub-assemblies. This first phase of the parametric design task has been described as design of the design or meta-design (Burry, 2006, 2003). There are differences in views on how much of the problem structure needs to be understood at this stage.

Once a representation has been constructed the task involves manipulating this model or transforming the functions to develop an appropriate design solution. This is seen as a process of exploration where, through the generation and evaluation of alternative designs, the designer visits portions of the solution space. The evaluation of each alternative guides further direction in the solution space or may suggest adjustment of the original constraints and requirements. Adjusting these is equivalent to redefining the boundaries of the solution space.

3.2.1 Creating the model

Developing a problem description

The initial task is to develop an understanding of the design problem at hand and to express this in terms of parameters. Motta & Zdrahal (1996) describe in broad terms the basic starting process; the key parameters must be identified, initial legal values assigned and valid ranges established. The parameters are established by identification of functions or requirements to be delivered and the constraints to be satisfied (Chandrasekaran, 1990). Chandrasekaran also notes that "many parameters do not contribute to the size of search space" and suggests that key parameters can be identified as a result of task knowledge.

Gero (1990) acknowledges the identification of functions, constraints and requirements by using three formal categories. "function, structure and behaviour" which together form a "design prototype".

1. Function relates to the intention or goals of the artefact.
2. Structure concerns the parts or components that the artefact will comprise of.
3. Behaviour concerns that way in which the structure achieves the function.

For example the study undertaken by Thamn *et al.* (1990) illustrates the process of window design using these terms. Some of the functions of this problem are to provide daylight, control noise and provide views. The structure in this design problem comprises of glass and frame. The structural components have variables such as frame dimensions and glass coatings which determine their behaviour. Two of the behaviours of the structure are light flux transmitted and sound reduction.

Design prototypes are dependant on the constraints of knowledge of the object of the design study (Coyne *et al.*, 1990). Coyne *et al.* consider prototypes as design from which other designs originate. Three ways that prototypes can be applied are proposed; refinement, adaptation and creation. In the case of refinement, design is limited to the constraints of the knowledge and involves changes within the design space that the knowledge defines. Adaptation is concerned with slight changes to the design space by adding further knowledge to that which exists. Lastly the creation of prototypes is where a new design emerges but Coyne *et al.* suggest that even new prototypes are developed through adaptation.

Externalising ideas, constructing a model

Given an understanding of the design problem, an initial starting point for the process is required. Four categories of design initiation methods can be identified in the literature; informal ideas, formal descriptions, abstract computational constructs and partial solutions.

Informal ideas can indicate initial design directions. These can be found by drawing an analogy between the current problem and previous solutions or ideas in the designers memory and has been described as "recall" (Woodbury & Burrow, 2006).

Formal descriptions of problems have also been described as a means of establishing a design process. The design prototypes proposed by Gero (1990) are this type of starting point. The prototype is a means of representing knowledge, it is not regarded as a design in itself but a sophisticated problem description. Design with prototypes is initiated through retrieval of a previous prototype or by specifying an initial set of function, structure and behaviour. This starting prototype is based on analysis of the client's functional specifications which indicate a suitable start point. The initial structure is based on an existing solution or a solution from a similar problem. The retrieved prototype is then adapted to suit the new problem. The adaptation is based on analysis and knowledge of the new condition, the adapted prototype then becomes the starting point for the design problem.

Abstract computational constructs are also described as ways of launching the design process. These may be selected from formal libraries like the repository of design patterns (Woodbury *et al.*, 2007; Woodbury, 2007), or the "referents library" described by Iordanova (2007). These will represent some part of the design problem. An example of such a starting point for design from the Design Patterns Repository is the "Jig". This demonstrates to a designer how to "build simple abstract frameworks to isolate structure and location from geometric detail." (Woodbury, 2007). It consists of a series of alternative models built using a commercial parametric modelling package. Each model is documented, including descriptions using four headings; intent, when, why and how to use it. The intention of libraries like Design Patterns is to offer parametric starting states that are then adapted by the designer to suit specific problems.

Chandrasekaran (1990) suggests two methods for selecting an initial design proposal. These can be regarded as designs that partially suit the current problem description. The first method is described as case retrieval the second is called decomposition-solution-composition. Case retrieval involves obtaining almost complete design proposals by searching a memory bank of previous cases until a design is found that solves a problem similar to the current one. This is equivalent to prototype refinement or adaptation proposed by Coyne *et al.* (1990). The decomposition-solution-composition method generates design proposals through decomposing problems, solving independent parts and then re-composing to form an initial solution. The design proposals resulting from both of Chandrasekaran's methods are then evaluated to see if they satisfy the functional requirements of the problem.

The initiation of the design process is described by (Motta & Zdrahal, 1996) as design state selection. Typically this involves selecting a design from a portion of the design space already searched. It, like other processes already described, includes the possibility of a designer selecting a starting state from previous experience. Like Chandrasekaran's design proposals these are regarded as partial solutions to the current problem.

Once an idea of the problem structure has been developed and some kind of starting point proposed these are then be used to create a representation or parametric model. Kilian (2006a) suggests that the process of constructing a design model or representation is about externalising ideas and capturing expertise, experience and constraints. The notion of models capturing understanding or knowledge has been explored by Williams & Hudson

(2009). Aish & Woodbury (2005) describe this process as explicitly developing relationships between objects and capturing these within some software. If relationships or objects do not exist within the software the user must be able to create bespoke tools for the design problem. The process of making the parametric model has been described as designing and constructing a control rig rather than the geometry of the object itself (Aish, 2005).

For Burry (1999) the process is about declaring parameters rather than shape. As an abstract example Burry uses a circle that is described as an ellipse with coincident foci points. The positions of the foci are parameterised, moving them apart causes the circle to become an ellipse. In a more practical example, Burry's work on the Sagrada Familia (Burry, 2003, 2006) (dealt with in more detail in chapter 4) was concerned with parameterising the family of geometry that Gaudi had worked with, rather than simply recreating the forms. This is thought to allow the continued construction of undocumented parts of the Sagrada Familia in the style of Gaudi.

Key to establishing a model of the design is devising a composition, a sequence of parts that together form the whole model. Aish (2005) sees the process of developing and refining composition strategies as an important task. The process of composition or decomposition extends ideas described as fragmentation in the previous chapter. Coyne *et al.* (1990) propose that design goals can be decomposed in order to assist the process of goal satisfaction. Aish (2005) describes it as involving the breaking down of a building into sub-systems and components.

Chaszar & Coenders (2007) describe two possible options for composing parametric models; top-down and bottom-up. In their top down approach a global geometry is defined which informs the position of components. The bottom-up approach begins with the definition of components or sub-assemblies which interlink to form a global geometry. Gero (1990) and Thamn *et al.* (1990) describe fragmentation as partitioning. Defining partitions is largely dependent on the designer's experience of the particular design problem. Once partitions are defined then only information relating to them is used to solve that part. This reduces the space within which a design will be found.

The process of model construction requires some form of abstraction of the design and developing a representation of this. Simon (1973) suggests that the use of multiple representational methods would assist the design process, and that switching between modes of representation would help designers see problems in alternative ways. Kilian (2006a) extends these ideas through his descriptions of the benefits of non-geometric representations to help develop understanding of problems and observations of the insights gained in translating between representations.

3.2.2 Exploring the design space

Given a detailed understanding of the problem structure and a means for representing this, the task becomes one of exploration of the design space. Kilian (2006a) regards exploration as the primary task for the designer. Exploration can be achieved by constructing a constraint explorer. Designing with a constraint explorer involves varying the constraints and objectives as part of the process. A constraint explorer is a computational environment for designing based on constraint descriptions. Gross (1985) views design as exploring "objectives", or "relations". For Kilian, exploring the design space also involves change of both solutions and problem descriptions. Kilian adapts the constraint explorer term to "design explorer" which is defined as "a physical or computational construct that combines design representations and constraints in order to support design exploration within the defined conditions." Parametric software is one tool amongst others that can be used to construct a design explorer. Chandrasekaran (1990) describes the process of exploration as a search in a space of sub-assemblies and one key objective is to develop strategies that reduce the search space to make the design process more practical.

Find appropriate values for parameters.

The design exploration task begins by a process of assigning values to parameters in accordance with given requirements and constraints (Motta & Zdrahal, 1996). Aish (2005) suggests the parametric designer should know what are valid inputs. For Gero (1990) exploration is about seeking which variables might be appropriate, and in doing so, transforming a set of functions into a design that can achieve these functions. Burry (2003) claims that all design tasks are concerned with evaluating a range of parameters.

Generation of alternatives

Design exploration is about the generation of multiple options or alternatives. Woodbury & Burrow (2006) note how the production of alternatives has been observed by Akin (2001). Akin observed the generation of alternatives amongst experienced designers. The Woodbury and Burrow describe the construction of paths into the design space as the main task in exploration. Further exploration along that path is conditioned by knowledge of the current design and other designs that can be reached from it.

Assessment of Alternatives

Following the generation of a design proposal, the solution must be assessed to establish its appropriateness. Aish (2005) suggests the parametric designer should be able to interpret, verify and validate any results of a design search.

Chandrasekaran (1990) describes his design method as Propose-Critique-Modify (PCM). The "propose" part of this method has been described above (case retrieval and decompose-solution-compose). PCM is concerned with assessment and then change, based on the results of assessment. In order to critique a proposal it is first verified to ensure that the proposal satisfies functional and other specifications. If functions are not satisfied, the proposal is modified accordingly. If verification is positive, the proposal is then critiqued. This is a diagnostic process where areas of failure are identified. The way in which a design fails directs the modifications that are subsequently made. This may include incremental improvement of parameters, or adjusting the dependencies of the model. Critique may also indicate a required change to the functional definition of the model.

Motta & Zdrahal (1996) describe a method of parametric design as "Propose and Revise". It is similar to the PCM method described by Chandrasekaran and involves selection of a design state (described above). The original is then adjusted by selecting and applying an "operator" and finally evaluating the new model. Four criteria are then used to evaluate the design; feasibility (whether it can lead to a solution), cost, completeness (whether a complete solution is generated) and consistency (whether any requirements or constraints are violated).

The PCM design model and the Propose and Revise method illustrate the iterative nature of the parametric design process and the close relationship between generation and assessment of alternatives. Generated alternatives are evaluated, this informs adjustment of the original, which leads to a new alternative.

3.3 Considerations

Parametric design tasks have been identified from literature and fall into two broad categories; the process of model creation and then using this model to explore the design space. In this section considerations described in the literature are identified and described. Considerations were defined in the introduction as something that a parametric designer keeps in mind when making a decision or facts related to the task they are undertaking. The tasks described in section 3.2 are used to organise this section and considerations suggested in the literature for that particular task are described.

3.3.1 Creating the model

Develop the problem description

In order to develop an understanding of the design problem, Kilian (2006a) suggests using domain mapping, which is a diagramming process. In this way the problem can be analysed to find existing constraints and degrees of freedom. The degrees of freedom are the number of values that can vary in the final set of relationships, finding these is concerned with identifying parameters. Kilian suggests a function based analysis, as a component based analysis could limit exploration to dimensional variation. Kilian's thesis investigates constraints as a positive force that can be used as drivers for design ideas. This extends a notion also expressed by Gross (1985) and described by Burry (2006).

Chandrasekaran (1990) believes that the descriptions of functions and constraints can be incomplete at the outset but that they will develop in the course of the design. Chandrasekaran describes the need to consider the complex dependencies when working on decomposing a problem. Further to this Chandrasekaran states that the order in which sub-tasks are tackled will have an effect on the outcome and therefore requires consideration. Aish (2005) suggests that multiple alternatives for decomposition may exist and that different versions may be more suitable depending on the design stage. He suggests that ways need to be established for approaching the process of breaking buildings down into sub-systems and components.

Literature reviewed in this chapter has suggested that parametric design can help form a better understanding of the problem. In order to develop a parametric model, some form of problem description is required. This chapter has identified views that suggest this description does not need to be a complete description (Gero, 1990; Chandrasekaran, 1990). Parametric models based on incomplete problem descriptions are believed to allow designers to develop their understanding of the problem. A better understanding of the object being designed can result from the additional effort required to develop a parametric model (Aish & Woodbury, 2005). Once a parametric model has been developed, Gero (1990) sees the process of exploration as an opportunity for the designer to learn about emergent features as the design proceeds. The suggested methods; "Propose-Critque-Modify" (Chandrasekaran, 1990) and "Propose and Revise" (Motta & Zdrahal, 1996) demonstrate an opportunity for parametric design to develop problem understanding. When a parametric model is used iteratively to generate and test designs, new knowledge of the design problem can be acquired.

Fragmentation has been described as a means for simplifying the parametric design task by breaking a problem into more manageable parts. It is regarded in the literature as a necessary process. Developing and working on alternative sub-parametric models can lead to alternative problem descriptions. For Gero (1990) and Thamn *et al.* (1990) fragmenting (partitioning) of a design problem allows it to be seen from various perspectives.

Externalising ideas, constructing a model

In initiating a design process, ideas have been described in the literature as originating from one or a combination of sources. These have been identified as; informal ideas, formal descriptions, abstract computational constructs and partial solutions. Each of these is discovered by selection from some form of memory. Chandrasekaran (1990) suggests that the ability to select a suitable starting model, one that resembles the current design problem, is dependent on the individuals experience or knowledge and their memory of previous designs. He suggests indexing cases to assist in selection of good matches with the current problem. Two alternative indexing systems are proposed; using a vocabulary of features and the goals related to the case, or indexing cases using function. Woodbury & Burrow (2006) call the process of selecting a design idea held in memory “recall”. This should operate on both whole and part models. An example of “whole recall” is the reuse of a design for a complete office building whereas the use of a window detail would be “part recall”. The ability to use part or whole descriptions is important for Gero (1990), the design prototypes he describes are based on retrieval of part or all of a previous prototype.

Aish & Woodbury (2005) have claimed that parametric model building requires the designer to consider the underlying principles and relationships rather than the appearance of the geometry. Aish (2005) also suggests that design is about making inspired creative decisions with incomplete knowledge of the problem. The notion that a parametric model can be assembled by starting with an incomplete description of the problem has been mentioned by Motta & Zdrahal (1996), Chandrasekaran (1990) and Gero (1990). In the constraint explorers described by Gross (1985), constraints can be prescribed in whole or part and added to as necessary.

A contrary opinion regarding the completeness of problem description is held by Burry (2003) and Maher (2006). For them the development of parametric models is a process, where everything needs to be considered at the outset. Two particular aspects of this that Burry has commented on are indeterminacy and naming conventions. Burry proposes that parametric models should be developed to include factors of indeterminacy. An example that Burry describes is a parametric model that includes the ability to add vertices to a polygon. In this model it was not necessary to consider scenarios where vertices were removed as Burry believes the computer is more capable of handling absence than super-presence. Burry (2006) stresses the need to consider naming conventions in the design of shared parametric models. Where conventions are clearly established the model can aid collaboration, whereas without convention the model will hinder it.

The parametric design role involves several more considerations than a standard design role. These increased overheads are discussed by Woodbury & Marques (2006). Parametric design is seen as increasing the complexity of a modelling task by requiring a greater level of description and control.

The parametric model is a representation of the problem space. Woodbury & Burrow (2006) suggest that when constructing one, designers should focus on the problem rather than becoming too concerned with programmatic issues. The representation should be intentional, which means it is an abstraction of real objects. The designed object will concern phenomena beyond the reach of the chosen representation, such as the effect of light and space on architectural geometry. Design decisions are often made based on these un-represented aspects of the design. Such aspects, Woodbury and Burrow suggest, will be recognisable in an instantiation (such as a physical model or radiosity processed visualisation) of the design. It is important for the designer to distinguish between these unrepresented and represented properties.

Woodbury and Burrow suggest that both strong and weak representations should be used. When a representation has the ability to demonstrate some physical properties of an object it is considered strong. An example of this would be including light absorption qualities of a material, these kind of properties can be described algorithmically. A three dimensional model in a rendering package is therefore a strong representation as it includes some level of detail of the way light interacts with the object. When the representation is used as a reminder or hint (such as a hand drawn sketch) it is considered weak, but the suggestion it makes may trigger a design insight. To use representations they must carry properties from outside and as such they will need to change during the design process.

A good representation is one that supports change (Woodbury & Burrow, 2006). Woodbury and Burrow also recommend that representations should be partial. An example of a partial representation is a sketch, since it does not suggest everything is known about the design but still represents it. Using a computer aided design tool can force the designer to commit to details. Woodbury and Burrow warn against this, as committing to specific detail too early in the process can restrict later change. A partial representation is still intentional, it is an abstracted version of a real object, but can be about part of an object that can be added to and subtracted from.

Kilian (2006a) notes how the more complex the representation, the greater the abstraction, and therefore the further the designer is from the object being designed. Aish (2005) acknowledges this but also notes that new possibilities reconnect the designer with the object. This is achieved through direct output of physical form from abstract models using computer controlled fabrication machines. Kilian (2006a) claims multiple representations can assist the design process. Kilian also places great emphasis on use of non-geometric representations as this will allow multiple factors that influence and constrain the design to become part of the design process.

Parametric tools are limited by their hierarchical structure, which needs to be specified early in the process (Kilian, 2006a). This restricts change to other structures which can prematurely freeze the exploration process. The hierarchical structure also encourages the user to develop long chain geometric dependencies. These can make a model computationally heavy and slow to update after parameter adjustments which can limit the designer's desire to change the model.

For similar reasons Burry & Burry (2008) recommend that parametric modelling takes place once conceptual ideas have been resolved. They believe that radical change in early design phases is crucial and no relational system can be flexible enough to incorporate this. Once a model is constructed they acknowledge the ability of parametric models to involve the human as a mutli-criteria optimiser through simple hand-eye coordination.

3.3.2 Exploring the design space

Find appropriate values and generation of alternatives

The task of finding appropriate values can be inhibited by the enormous size of the solution or design space (Chandrasekaran, 1990). There are vast numbers of alternative design solutions. The design exploration therefore takes place in a part of that space which is very small (Woodbury & Burrow, 2003). Even if a solution can be generated through intuitive processes it should still be evaluated, critiqued and modified, therefore moving to another part of the design space (Chandrasekaran, 1990). The size of the solution space leads Motta & Zdrahal (1996) to describe the design task as a complex decision making process, this emphasises the need to develop ways of reducing vastness. Woodbury & Burrow (2006) propose a series of designer "action amplifiers" which they consider to help exploration of design space and the process of generating alternatives. These are; informal representation, codification, explicit space, implication, backup, recall, replay and speed.

What Woodbury & Burrow mean by informal representation can be understood by considering solid modelling which gave designers just enough control to be creative without too many tool specifics which would over burden them. Codification refers to the use of script (application specific programming languages) within professional tools that allow the user to extend and automate tasks. Explicit space is the part of the design space that the designer has visited. By recording this previous work it becomes reusable and adaptable allowing it to become part of the libraries described above. Implication is the ability to explore what is implied by a set of rules. For example when a designer constructs a path into the design space, points along that path are explicit spaces (they have been visited). The knowledge of a point on that path and knowledge of the system allows the designer to know by implication what possibilities lie near by. Backup is the ability to go back to some previous design whereas recall is about finding a metaphor or precedent in the more distant past. Replay refers to the way in which a recalled source is combined into the current model. In their set of amplifiers Woodbury and Burrow describe speed as the time taken to make choices along a path of exploration. This is determined by the number of choices at any point, reducing choices increases exploration speed.

The literature reviewed in this chapter suggests that parametric design can assist in design investigations. Exploring the design space has been defined as a key task in architectural design. The nature of the parametric model is to allow change and facilitate easier exploration. It can therefore improve this part of the design process. Aish & Woodbury (2005) have recognised that parametric exploration can lead to a better developed problem description but also the discovery of new forms better suited to the design context. This is due to the ability to perform more thorough searches, which is made possible by the reduced time and effort required to make a change in a parametric model. Woodbury & Burrow (2003) consider the generation of alternatives to reveal aspects of the design that had previously not been considered. These new aspects provide the designer with a means of accessing more parts of the design space and will therefore find a better solution.

The process of parametric modelling involves the use of multiple representations such as geometry, symbols and script. Kilian (2006a) claims shifts between representations can trigger innovation by forcing effort in re-describing a design in different media. This can lead to discovering new ideas about a project.

Kilian (2006a) has suggested that using parametric design to construct control objects is an opportunity to more efficiently evaluate ranges of parameters. Parametric control objects are a geometric means for storing sets of multi-dimensional data that are accessed by further control parameters. A simple example given by Kilian is a cube that visually represents the space of possible solution parameters (figure 3.1). Within this volume a spatial point grid is defined and four lines drawn from each point to the lower corners of the volume. Properties of the lines such as length and the cartesian coordinates of the points are then used to define other geometric properties. In this example Kilian defines a range of vase forms. By adjusting the definition of the points within the volume the range of parameters can be broadened or focused on a specific range.

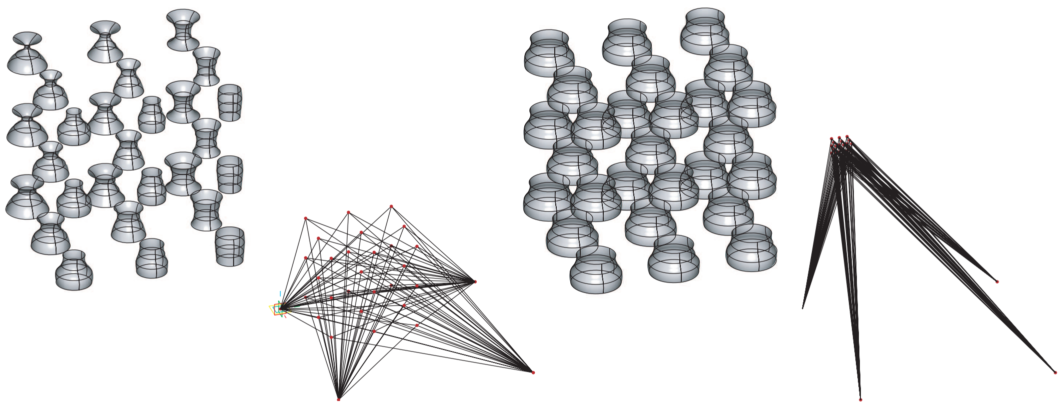


Figure 3.1: Parametric control objects.(Diagram recreated by author from Kilian (2006a))

Burry (2006) describes an opportunity in the way in which a designer with a parametric model can iteratively experiment with a design. In more traditional modelling processes this level of change would require deleting and recreating parts if not all the model, which would require the designer to remember or store a sequence of construction steps to make the model. Returning to previous designs would be counterproductive. The parametric designer is therefore able to move backwards and forwards by assigning and reassigning parameter values.

Assessment of alternatives

For Motta & Zdrahal (1996) assessment involves evaluation of feasibility, cost, completeness and consistency of a design. They describe the possible difficulty in extracting all this information from a design. Generally they believe that weak criteria may be the only way to assess feasibility of a model, making it hard to determine. For the same reasons design completeness is hard to evaluate. Assessment is directly linked to revision of the model. By assessing the model, the options for revision are indicated. Motta and Zdrahal describe these options as operators and one must be selected to improve the design. The designer chooses an operator based on the chosen design context and the specific design focus. The context describes the design goals on a more general level while the focus is a more specific goal within the context.

When evaluating a design (Critique) Chandrasekaran (1990) suggests that the designer should know about the way in which the structure of the design contributes to the overall behaviour. This knowledge is necessary for guiding the next step in improving the design (Modify). Modification either requires identification of what part or sub-system failed and how it failed or knowing what parameter to change to achieve the desired specification.

The literature reviewed in this chapter suggests that parametric models can be used to share data and assess designs. An opportunity suggested by Maher (2006), which assists the evaluation of the design alternatives, is to regard the parametric model as a communication tool for sharing the data. In this way a team of designers and construction specialists can assess the same model. Each individual whose task would be to focus on a specific aspect of the design and is able to manipulate the model and undertake analysis or assessment based on their specific design goals. Based on their assessment, each specialist could adjust parameters to modify the design within some predetermined range. Structural, fabrication and environmental implications and knowledge could be captured or linked through a framework of shared models.

To share a model in this way a good understanding of the design problem would be required in order to fully premeditate and plan the process. Burry (2006) has suggested that as part of this process particular attention is paid to the naming conventions for parameters. The purpose of this is to facilitate more efficient and easier sharing and management. Burry believes that a model constructed in this way with the specific aim of sharing has the opportunity to challenge the view of the architectural designer as the sole author.

3.4 Analysis

The intention of this chapter was to identify descriptions of parametric tasks and considerations through a review and analysis of literature. This serves two purposes, first to structure the way in which the practical literature and case studies are organised later in the thesis. Secondly, successful identification of these descriptions in the literature provides theoretic validation of the bipartite (tasks and considerations) that has been proposed as means of understanding the parametric design role.

The aim of this section is to summarise the review and, where possible, undertake analysis of the descriptions identified. A broad task structure was used in this chapter to organise the review of the literature. This was developed, based on descriptions of tasks identified in the literature. The task structure identified in this chapter is illustrated graphically in figure 3.2. This format is used throughout the thesis to summarise the findings from each chapter.

Descriptions of tasks and considerations have so far been treated separately. Typically the considerations relate to the broader set of tasks. Here, in summary, task and considerations are handled simultaneously to allow direct comparison. Also the simultaneous treatment allows contradictory opinions or descriptions of tasks to be compared and discussed along with the considerations that are related to these tasks.

3.4.1 Tasks and considerations when creating the model

Develop the problem description

Descriptions in the literature indicate that the first sub-task when creating the model is to develop the problem description. This is a process of parameter identification, and all the sources reviewed concur that this is fundamental to the parametric design process. The previous chapter showed that the general nature of architectural design problems is that they are ill-defined, therefore this is likely to be difficult at the outset of a design process. Parameters and constraints can be identified if the problem is effectively stated.

Kilian (2006a) has proposed that designers could consider the use of domain mapping or diagramming when undertaking the task of developing problem descriptions. He also suggests that constraints are treated as a design driver rather than an inhibitor. The opinions, in the literature regarding fragmentation in the design process agree that designers should consider that multiple alternatives can exist for segmenting design problems. The previous chapter established "fragmenting problems" as an natural approach to design. This involved decomposing a problem, addressing the parts, and re-composing them to form a solution. The literature on parametric modelling re-iterates these ideas and also confirms that the way in which sub-problems are tackled and that the order of re-composition should be considered as it will have an effect on the final solution.

Parametric design is thought to help form a better understanding of the problem. This suggests it would be beneficial for tackling architectural problems, the nature of which was described in chapter two. The need for formal representations of design ideas forces designers to consider the underlying principles of their design in greater detail, resulting in a more thorough understanding of the design problem. Contrary opinions exist. Burry (2003) and Maher (2006) believe complete problem descriptions are required before parametric modelling can begin, while others such as Chandrasekaran (1990),Gero (1990) and Motta & Zdrahal (1996) see the process of parametric modelling as assisting the designer in gradually developing an understanding of the design problem. This is particularly apparent when the model is used in an iterative design process where subsequent designs are generated, evaluated and modified. The fragmentation of models is considered a necessary task for most design problems, this too can lead to new ways that the designer can see the problem.

Externalise ideas, construct the model

The second sub-task begins with initiating the design process by using an idea based on the problem description. Views in the literature agree that this idea is sourced through a form of experience or memory. Specific descriptions of the type of idea and its source are varied. The ideas described vary from informal and abstract constructs to formal descriptions or partial solutions. These starting points are selected from some form of memory. Descriptions of the origins range from the human brain to formal code or model libraries. Although the descriptions vary they share the same origin, a notion of finding a starting point based on some form of experience or memory. This is consistent with the more general theories of design described in the previous chapter, where heuristics have been observed, in more traditional forms of practice, to initiate a design process.

It is suggested in the literature that some form of indexing could be considered as a means of identifying previous problem descriptions, making searching a formal library easier. When selecting from such a memory, the use of whole or partial existing problem description is considered beneficial.

The use of the term “memory” in the descriptions of this sub-task indicate the usefulness of both human and computer memory. In both cases, the role of the designer’s knowledge and experience plays an important role in accessing appropriate starting ideas.

After obtaining an idea, the second stage of this sub-task involves actually constructing the model. The construction of parametric models is described in the literature as a process of developing and capturing relationships with software. If the necessary means for modelling these do not exist, they must be constructed by the designer. The task is about constructing control mechanisms and relationships rather than the geometry of the object. The process of thinking about and explicitly constructing relationships and control devices was not found in the literature reviewed in the previous chapter. It is a new design task that is necessitated by parametric design.

Fragmenting design problems was identified as a part of a more general design theory in the previous chapter. This chapter has also identified the task of fragmentation of the modelling process, which is recognised and discussed in literature. The purpose of this is to break the model into a sequence of stages that can be addressed semi-autonomously. The previous chapter described how this broke tasks into more manageable conceptual chunks. The literature suggests this is also possible for the parametric model and the same considerations are relevant. The order in which the chunks are tackled and later re-composed should be considered because they have implications for the final model.

In the literature there are several references to considerations that should be made when externalising ideas and constructing the model. Designers are urged to consider the underlying principles and relationships rather than the final geometry. It has been recognised that this can make the task more complex and the extra time required should be considered when undertaking parametric design.

The need for, and use of, multiple modes of representations is identified as a key consideration in the literature. This is consistent with the views expressed by Simon (1996) that were described in the previous chapter. While the use of multiple representations may benefit the design process, parametric designers should consider the trap of becoming too concerned with programmatic issues rather than design. Similarly, more complex representations are described as increasing levels of abstraction that can distance the designer from the object being designed.

3.4.2 Tasks and considerations when exploring the design space

Generating alternative designs as a form of exploration was identified and observed in the reviewed literature of the previous chapter. This need for exploration is reiterated in literature reviewed in this chapter.

Find appropriate initial values and generate alternatives

The first sub-task of the exploration process is identified from the literature as assigning initial values and evaluating parameters. The designer constructs paths into the solution space by adjusting the values assigned to parameters and storing the points visited along that path. The use of constraint or design explorers is described as a way of exploring design spaces. Parametric models were shown to be useful in constructing certain elements of these.

The size of the solution space is described as vast. It is suggested that designers consider means of reducing the design space in order to make the problem simpler. Woodbury & Burrow (2003) suggest that designers consider various strategies that they believe amplify exploration actions. These include informal representations, codification, explicit space, implication, recall, replay and speed.

One of the goals of constraint explorers is to allow changes to both design solutions and problem descriptions. The hierarchical structure of parametric software is described as limiting the possibility for changes to the problem structure. This is due to the time and effort required to reconfigure relationships in the model and the difficulty in dealing with cyclical relationships. In complex parametric models the hierarchical structure can result in long chains of geometric dependencies. These can restrict the designer's inclination to make changes due to the length of time required for the change to propagate throughout the model.

Parametric models are concerned with exploration. They define a solution space and present an opportunity to improve design exploration by performing more thorough searches within the solution space that it defines. This is due to reduced time and effort required to make changes to the model. The result is an opportunity to discover new forms which are better suited to context. Working with and switching between the different types of representation required for parametric design is a further opportunity to discover new ideas about a design. Developing new forms of parametric control objects is an opportunity to efficiently evaluate ranges of multi-dimensional parameter sets.

Assess alternatives

The second sub-task of the exploration task is the assessment or evaluation of alternatives. The designer must interpret, verify and validate the results. Evaluation of the design involves checking it satisfies requirements and identifying what can be changed in order to improve the next solution.

The process of assessment requires the designer to consider both the way in which the evaluation is undertaken and the way in which they respond and make subsequent changes to the model. The criteria on which the assessment is based and the way in these are extracted from the model need to be considered. This may require the parametric designer to consider the assessment procedure early in the model construction task. Evaluation will indicate how to modify the design, the designer's knowledge of the problem structure is required to identify this.

Assessment opportunities are enhanced by the possibility of having shared models that various specialists are able input data and control geometry in response to analysis. The parametric model can be regarded as a communication tool for sharing data between multiple designers and construction specialists. A shared model requires a high level of pre-meditation in terms of conventions. Models that are shared have the opportunity to challenge the view of the architectural designer as the sole author.

This critique of parametric software suggests limitations for parametric design. The previous chapter proposed that initial ideas were used to structure the problem space and in doing so reduced the search. The parametric model represents a description of the problem and therefore structures the space and reduces the search. Reduction in problem space was described as a design goal in the previous chapter. Limitations can be overcome provided the designer is aware that the parametric model narrows the range of solutions and understands the scope of possibilities that it defines. The parametric model can therefore assist, rather than constrain design explorations.

3.5 Summary

This chapter establishes theoretical descriptions of tasks and considerations. Succeeding chapters seek practical evidence for these descriptions first in literature from practice and then in case studies. These theoretical descriptions also provide an initial theoretic basis for the bipartite that has been proposed in order to understand the role of the parametric designer. These initial task descriptions are represented on the parametric task structure in figure 3.2. This diagram is used to graphically summarise the findings of each chapter and subsequently appears empty at this stage.

The initial definition of parametric design task is broken into two parts; creating the model and exploring the design space. Creating the model requires developing the problem description, which is an iterative process. Some initial ideas instigate the design process and suggest some form of abstraction. By focusing on relationships and control method a parametric model can be constructed and studied. Exploring the problem space requires finding values for parameters and generating alternatives, which are then assessed. The

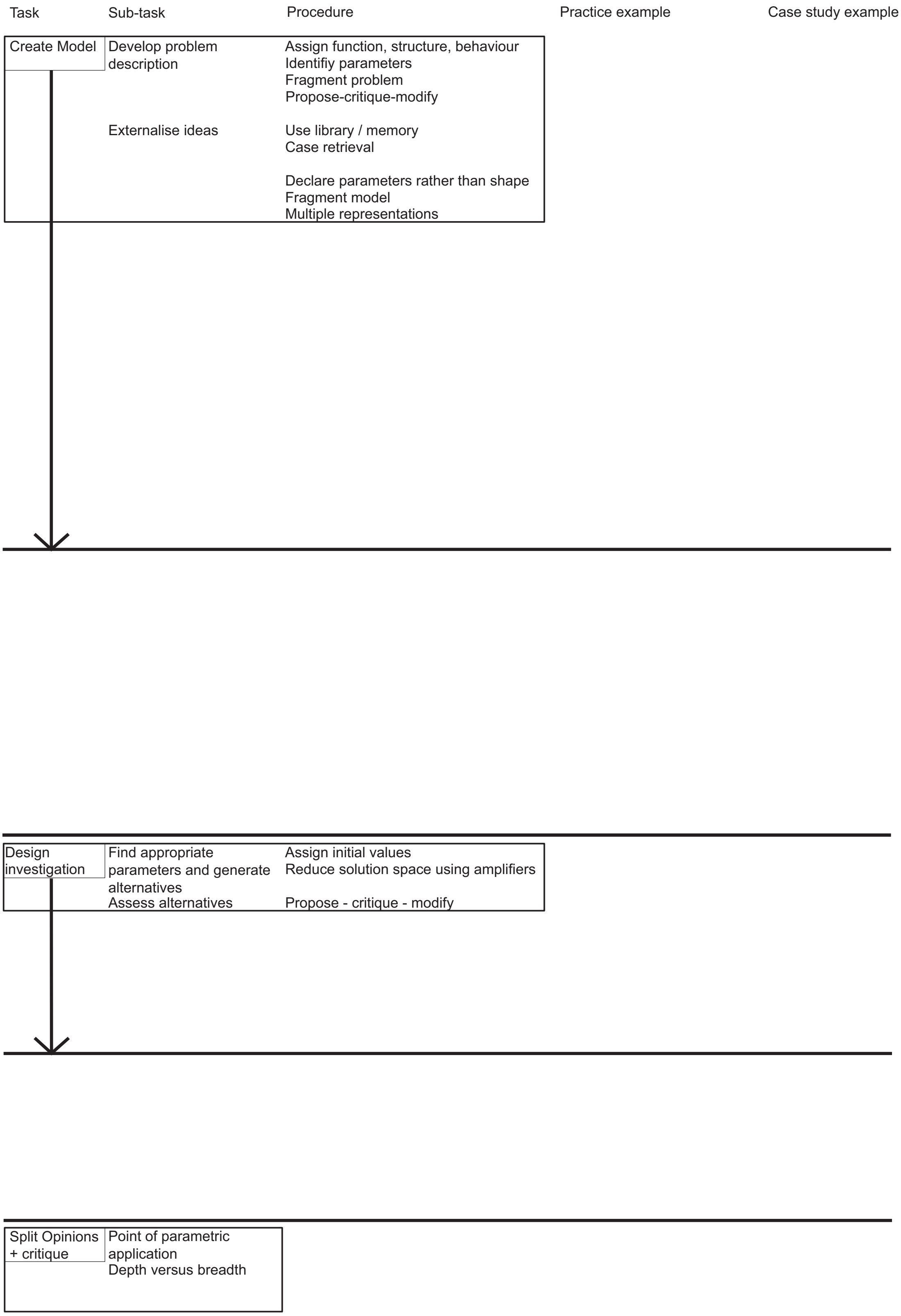


Figure 3.2: Task structure.

designer then returns to the original problem description and adjusts according to their findings or they refine selected variables and generate the next alternative.

These task descriptions are supported by opportunities for parametric design identified in the literature. It is suggested in this chapter that parametric design offers the opportunity to develop a better understanding of the problem. This addresses the difficulty defined in the previous chapter of describing architectural design problems. A second opportunity identified is that the parametric model can assist with design exploration. This is dependant on the designer understanding the way in which the parametric model structures the problem space. Lastly it was suggested that parametric design can assist in sharing and evaluation of models. This stems from the need to externalise ideas and capture knowledge in the process of defining a parametric model. Removing internal design processes means that more people can be involved and the model can be more readily shared and subjected to wider assessment.

The literature identified two further items that feature in the task structure under the heading split opinions and critique (figure 3.2). The split opinion relates to discussions on the point at which parametric design is applied in the design process. Two approaches have been noted. The first suggests that parametric design should begin as early as possible and can help the development of a design. The second proposes that the parametric model is restrictive in the breadth of possible exploration and that it should be developed after early design phases. The reasons behind this contrary opinion also forms a critique of parametric design, that the hierarchical model structures enable depth of exploration at the cost of breadth.

The next chapter therefore seeks practical evidence of the tasks and considerations to validate the initial descriptions established in this chapter. This evidence is sought through analysis and review of literature originating from design practice. In addition to seeking evidence to support theoretical descriptions of the parametric role established so far, further descriptions of the role may also become apparent.

Chapter 4

State of practice

4.1 Introduction

This chapter is a review of published material originating from architectural and engineering practice. The primary aim of this serves two purposes, the first is to continue to develop the suggested bipartite; tasks and considerations which is proposed as a means for understanding the role of the parametric designer. The second purpose is to seek evidence in the form of practical examples that validate the tasks and considerations found in the review of theoretical literature in the preceding chapter. Practical evidence is seen as validation that theoretic descriptions have practical application.

In reviewing literature from practical origins it is possible to assemble a description of the position of the parametric designer in practice. This is done by identifying the nature of parametric work, how this relates to the design team within the practice and how information generated by parametric designers is conveyed to the broader design and construction team on a project.

The diagram in figure 4.1 depicts the thirty-two projects from ten practices or consultancies that provide parametric services to practices. The time frame for all the projects discussed spans nineteen years. The diagram is intended as a reference for the reader. When a project is referred to in the text in this chapter, its name is *italicised*. The number that follows is used to reference it in the task structure at the end of the chapter (figure 4.27). In this way the reader can refer to the diagram for the basic information about each project. In addition the reader can refer to the glossary to find the page where the project is first mentioned. It is important to consider that the project start and end times do not necessarily reflect time span of parametric design involvement. And that other projects involving parametric design exist, but these are not included as sufficient published material does not exist.

The first section of this chapter deals with the position of the parameteric designer in the design office and introduces the practices reviewed. Next, descriptions of the identified tasks and considerations (made when the tasks are undertaken) are given. In the analysis section the descriptions of position of the parameteric designer in the design office are used to determine a set of generic workflow models that locate the role within the broader context of the project. Descriptions of tasks and considerations are then analysed and compared to the existing framework established in the previous chapter. Evidence supporting the existing framework is summarised and goals for the case studies following this chapter are described.

4.2 Position of parametric designer in practice

The practices studied are from both engineering and architectural disciplines and include independent consultants providing parametric design services at all stages of the design process. Four common strategies for positioning parametric design within the design office are observed in the published material; consultancy groups within practices, independent consultants, integration with design teams and undetermined position. The size of some practices allows more than one of these structures to be in place. While other practices do not commit or comment on the position of the parametric design role, but have published material that suggests it plays a part in their office. These are described in a fourth category as undetermined position.

Figure 4.1: Parametric projects time line.

4.2.1 Consultancy groups within practice

A consultancy group within a practice is the most commonly reported model of positioning parametric design skills in practice. This model has been adopted by both architectural and engineering firms.

Architecture groups

The most widely published architectural practice on the subject of parametric design **Foster and Partners (FP)**. FP's Specialist Modelling Group (SMG) is a research and consultancy group within the practice, one of their specialities is parametric design. The group was established in 1998 and is currently led by Hugh Whitehead. The group is involved in project driven research and development involving project workflow, three dimensional modelling and creation of custom tools for the practice (Peters & De Kestelier, 2006). Specialists within the SMG also claim to work with project teams on either a short or long term basis and are involved from concept design to fabrication. Although there is little evidence of this in published material.

Members of the group are skilled in design, mathematics, geometry, computing and analysis. Their work is described as not being concerned with proposing form but searching for ways of describing these forms. At the SMG, parametric modelling typically involves extending Bentley's Microstation using Visual Basic for Applications (VBA)(Peters, 2007). Whitehead & Peters (2008) consider the SMG at Foster and Partners to be the first specialist geometry group within a contemporary architectural practice, a model, they claim which other practices have followed. FP use a means of conveying geometric data with other specialists and manufactures described as the Geometry Method Statement (GMS). This is in the form of a series of diagrams and text descriptions of how to recreate the geometry (Whitehead, 2003; Peters, 2008). This statement is issued to contractors who are required to follow the description to recreate the geometry.

Brugger (2009) describes three groups at **SOM** concerned with parametric design and operating as internal consultancies and research groups the Digital Design Group (DDG), the Advanced Design Group (ADG) and Blackbox. At SOM the role of parametric designer is more concerned with production or efficiency than relationships or geometry. The DDG is responsible for implementation of new CAD technologies and primarily using REVIT (Autodesk, 2008). The DDG is a highly structured group which includes four distinct roles. Digital Design Directors (DDD) oversee all the efforts of the group and define directions for improvements in the office related to new technology. Digital Design Managers (DDM) manage projects and Digital Design Coordinators (DDC) coordinate links between the practice's design groups (undertaking design development and 20% of construction documentation) and the technical groups (responsible for the full construction documentation stage). Lastly Digital Design Specialists (DDS) undertake the task of constructing models. The ADG focuses on sustainable design, they work closely with SOM's mechanical, electrical and plant groups.

SOM's Blackbox group is primarily concerned with research and development. Their focus is to make tools to improve the preliminary design process using skills in parametric modelling, geometry, scripting and analysis software. The conduit by which SOM's parametric designers relate to the wider construction team is the digital model. They use the Building Information Model (BIM) software such as Digital Project (GehryTechnologies, 2009) and REVIT (Autodesk, 2008).

Engineering groups

Buro Happold (BH) operate two internal constancy groups in the UK. Software Modelling Analysis and Research Technology (SMART) and the Generative Geometry Group. Both provide parametric and generative geometry support to other project design teams within the practice and external architectural clients (Fisher, 2009). SMART also undertake finite element analysis, non-linear structural analysis, form finding and optimisation. The SMART group consists of a team of engineers and programmers who take logic from architects and capture design ideas as computer code. (Winslow *et al.*, 2008a,b). Sharma (2008) discussed the general tasks of the SMART group; mapping grids, pedestrian flow simulation, bomb blast simulation, grid solutions using dynamic relaxation and rationalisation of architectural design. As they are based in an engineering practice a key task is the production of data files for structural analysis and structural geometry for contractors. These originate from a coded parametric definition. Typically they create their own software as plug-ins to Rhinoceros

(McNeel, 2007) which gradually get extended as the need arises. They also produce full electronic scheduling and create digital fabrication interfaces (Sharma, 2006).

Members of the Generative Geometry Group within BH come from architectural backgrounds. They operate as an interface between architects and engineers by providing techniques that allow complex buildings to be engineered and realised (El-Ali, 2008) using parametric software.


Figure 4.2: Serpentine 2005

Within **ARUP**, parametric design tasks are undertaken by the Arup Advanced Geometry Unit (AGU). The AGU is a mix of architects, engineers and computer scientists acting as a consultancy within ARUP. The group's primary role is to research complex structural geometry that can support architectural visions and solutions (AGU, 2008). They undertake their own design work and also collaborate with architects and designers. Their work on two summer pavilions *Serpentine 2002 (18)* and *Serpentine 2005 (19)* (figure 4.2) demonstrates a working process focused on capture and development of rule based systems using script or code. Their role includes production of detailed information for the manufacture of parts. The group's primary concern is to find solutions, rather than rationalise problems proposed by architects.

Within **Adams Kara Taylor (AKT)** p.art (parametric applied research team) undertake parametric design tasks (AKT, 2008; Hanif & Anstey, 2008). Their work is split between developing parametric construction solutions with Digital Project and the research and development of a toolkit of methodologies that can be customised in order to suit specific projects.

4.2.2 Independent consultancy

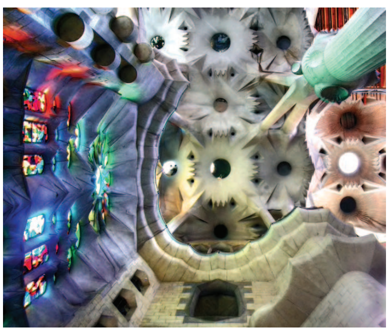


Figure 4.3: Rose window and ceiling at the Sagrada Familia

Mark Burry has acted as an independent consultant on the continued construction of the *Sagrada Familia (3)* (figure 4.3). In order to continue construction Burry has been involved in parameterising the geometric methods Antonio Gaudi used (primarily ruled surfaces) (Burry, 2006, 2003). The models are used to find geometric solutions by adjusting parameters to find configurations that fit partially completed elements. The model is then used to produce cutting information to drive CNC masonry machines.

designtoproduction (DTP) (2008) describe their role as one of rationalisation. They provide a service to transform curvilinear designs into assemblies of parts made from flat sheet materials and straight bars. They see their work as going from architectural design to machine code. They undertake this by extending standard CAD packages with application programming interfaces (API). They provide services to both architectural and engineering practices and work directly with manufacturers (designtoproduction, 2009) producing code to drive computer numerical controlled (CNC) machinery.

4.2.3 Integrated within design team

Brugger (2009) describes his role at SOM as a parametric designer. Together with two others with similar skills, they provide parametric modelling, performance analysis and verification support to a team of 15 designers. The design group is headed by a partner who doesn't believe in technical separation in architecture, subsequently he eschews SOM's established internal consultancies in favour of an integrated design group. In this design group parametric design plays a role from concept development to 90% completion of construction documentation. Parametric modelling is undertaken with Digital Project and geometry generated is shared with the design team as regular CAD files.

4.2.4 Undetermined

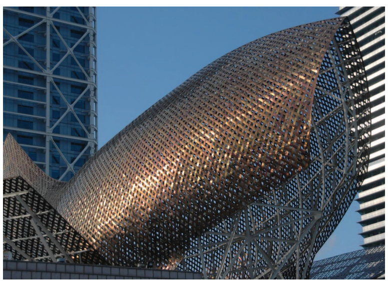


Figure 4.4: Barcelona Fish

At **Frank O Gehry and Partners (FG)** the design process is underpinned with physical modelling. This is followed by scanning and then rationalisation using the computer to remodel the original form. Parametric modelling has been used within the practice to find close matches between rationalised computer models and the original scanned data (Glymph *et al.*, 2004). Shelden (2002) has reported on the automation of repetitive CAD tasks and the use of bespoke modelling tools based around surface geometry that is achievable with sheet material. In the literature it is unclear if parametric designers are integrated into project teams or operate as internal consultancies. The *Barcelona Fish (1)* project (figure 4.4) is well documented (Lindsey, 2002) and the process used is thought to be indicative of later projects. The physical Fish model was recreated by Rick Smith, a consultant from the aerospace industry, using CATIA (Dassault, 2008). A parametrised surface was defined, that could be adjusted to find a close match to the original physical form. Smith also provided a service to various contractors to extract fabrication information from the model.

The parametric model created for the *Barcelona Fish (1)* project (figure 4.4) acted as a master document for the project, from which all construction information was generated. This master model or BIM is how the practice continues to communicate design information with contractors (Glymph, 2003). Based on their experience of this and later projects, a spin off company, Gehry Technologies was formed to develop software based on the CATIA aerospace package. The system, called Digital Project, includes parametric modelling and BIM tools.

Rick Smith later established his own business (virtualbuildteam, 2009) that operates as an external consultancy supporting Gehry's designers by managing the master models. Acting as consultant to the architects and nominated contractors, the model manager role involves extracting required information and insertion of new content (Lindsey, 2002).

Published projects by **Zaha Hadid Architects (ZHA)** have appeared in Journals dedicated to parametric design (Hadid, 2008c,b,a), but provide few details of the role of parametric tools in the design process or the impact of the technology in the practice. Illustrations imply that the projects involved some parametric technology but the use is not explicitly referred to. Additionally, the construction process of one of ZHA's buildings has been published (Grohmann & Bollinger, 2007; designtoproduction, 2008), suggesting parametric design is used by external consultancies to rationalise geometry and produce information for construction. However, Schumacher (2008) notes the formation of a computational design research group within the practice. Schumacher claims their work is research based and not as a specialist service group within the practice. The group primarily works with scripting using standard three dimensional modelling tools. These are used to generate component arrays and tesselations on surfaces and to investigate parametric urban models and high rise tower modelling. Schumacher claims parametric tools allow the practice to enhance the organic formal qualities of their designs. This is acheived through what he calls continuous differentiation, gradual change across an array of similar objects. He proposes that parametricism is a new stylistic movement in architecture like modernism. And suggests that Foster and Partners use parametrics to maintain modernist aesthetics while at ZHA they are interested in using the technology to emphasise possible variations.

4.3 Tasks

The descriptions of parametric tasks identified in practice are organised into five broad categories translation, rationalisation, control, generate and test, and sharing information.

4.3.1 Translation

The parametric translation task is concerned with changing from a non-parametric representation to a parametric model. This task requires an understanding of the problem or design task. This means knowing what is being investigated, what parts can change to enable the investigation and what is fixed. This understanding has to be extracted from the material or descriptions given to the parametric designer. Based on this the parametric designer can start to create a model to capture the process.

At the most simple level the process of developing a tool that automates a repetitive CAD task is a translation process (Shelden, 2002). The principles of the task being captured can be understood by observation of it being carried out manually. An example of this would be automating the process of measuring and storing the value of a panel width on a facade where panel widths vary. At FG, translation of design intent starts with physical models that are scanned, then a computer model is constructed that aims to capture the same geometry. Where this has been undertaken parametrically (Glymph *et al.*, 2004) a model is defined that allows parameters to be adjusted by designers to try and match the scanned geometry.

Figure 4.5: Futuropolis

Automating repetitive tasks requires the designer to capture the basic process as a set of repeatable rules or an algorithm. DTP (2008) were given an algorithm by Libeskind to generate the geometry of his *Futuropolis (16)* (figure 4.5), a wooden sculpture designed for a workshop held at the University of St. Gallen. Once expressed as a piece of code or script adjusting parameters and rerunning the script can generate alternative geometric configurations.

Burry's work on the *Sagrada Familia (3)* (figure 4.3) involves translating from physical models, photographs and sketches using known geometric techniques (ruled surfaces) to construct parametric models (Burry, 2003, 2006). This work involves using parametric tools to capture the working methods of Antoni Gaudi. Records of Gaudi's design and construction methods can be found in his built work, drawings and in incomplete or damaged physical models.

Dritsas & Becker (2007) translate traditional metrics of human perception into parametric versions. A theatre seating tool (Dritsas & Rafailaki, 2007) provides an analytic evaluation system that generates various measures of viewing comfort per seat based around horizontal and vertical view angles (frustum torsion), spatial occlusion (frustum culling), physical distance, visible volume and visible areas. The origins of this process are the sight-line method of setting out and evaluating seating layout. Changes to the seating geometry trigger update in the evaluation measures.

Figure 4.6: Smithsonian Courtyard

The development of the model for the *Smithsonian Courtyard (13)* (figure 4.6) is described as algorithmic (Peters, 2007). The algorithms used are based on an interpretation or translation of a rule set used and described by the design team to the parametric model builder. In both the *Smithsonian Courtyard (13)* and the *Elephant House (11)* initial ideas were investigated using more traditional CAD modelling methods and then later captured as algorithms (Peters, 2008).

Figure 4.7: Nanjing Station

Capturing design intent from a traditional CAD model and translating it to a parametric model also forms part of the work flow for *Nanjing Station (22)* (figure 4.7) (Gun, 2007a). Gun's translation tasks also involved transfer and translation between software applications. Some of his parametric models require scripts that export certain geometric information that then allow reconstruction in another application.

For AKT, translating or capturing design intent requires the identification of a set of relationships between the geometry of the project and its component parts. Based on this a parametric model is constructed. This is described as one of the tasks of the p.art team at AKT (AKT, 2008). Organising relationships between the whole and its parts is also the primary concern for DTP (2008). Architectural designs are not objects made from a single piece of material, they are assemblies of thousands of small parts. As a result, DTP approach their parametic design tasks by establishing project specific algorithms that relate the whole to its parts.

4.3.2 Rationalisation

The reviewed material shows a preoccupation with rationalisation. Rationalisation refers to the application of known geometric principles and construction techniques in order to realise a project. Post-rational is where geometry and construction constraints are considered after a conceptual design phase (Whitehead & Peters, 2008). When geometric method is rational from early design stages it is referred to as pre-rational.

Post-rational

Figure 4.8: Greater London Authority

Foster and Partner's *Elephant House (11)*, *Greater London Authority (9)* and *Sage (6)* are described as post-rational (see figures 4.20, 4.8 and 4.9) (Whitehead, 2003; Whitehead & Peters, 2008; Peters, 2008). These buildings began as free-form surfaces but project budgets and architectural criteria demanded planar quadrilateral mesh solutions. The task for the SMG is to find a geometric rationale that would best fit the original forms. *Greater London Authority (9)* was parametrised as a family of sheared cones, The *Sage* (6) as a series of tangent toroidal patches and the *Elephant House (11)* as a pair of toroidal patches. Torus patches and sheared cones are arc based methods that give planar quadrilateral panel solutions. The torus patch is also found in Foster and Partner's other built work [1].

Figure 4.9: Sage

Foster and Partners choose to use simple arc-based geometric compositions for their ease of communication and subsequent reduction of error (Whitehead, 2003). KPF seek to rationalise free-form surfaces to circular arcs for similar reasons. Hesselgren *et al.* (2007) also describe how these methods make communication to other members of the design team simpler. Rationalising surfaces to planar quad systems and grouping similar sized panels, which may be warped to specific tolerances forms a key area of work for KPF (Gun & Wallin, 2007). The *K3 Tower (25)* was post-rationalised and a cladding system developed involving planar panels that work like shingles (Gun, 2007a).

Matching original geometry with rationalised geometry and testing how well this matches is a major part of the design process at FG. The nature of the established design process is that it usually involves post-rationalisation (Glymph, 2003). Digital scans of physical models define a goal that computer modellers seek to match as closely as possible using rational geometry. The geometry of buildings such as Bibao Guggenhiem and Disney Concert Hall required surface geometry that could be covered with flat sheet cladding materials. Geometry described by physical models was therefore rationalised according to this criteria. The *Museum of Tolerance (2)* is documented as being rationalised using parametric design (Glymph *et al.*, 2004). Here a type of surface producing planar quadrilateral solutions known as a scaled translation surface was parametrised and adjusted until it matched the original scan. This system generated four-sided planar cladding panels. These are described by Glymph *et al.* as desirable from an economic point of view as there are fewer machining operations and fewer mullions.

[1] See Canary Wharf Station, London and the Imperial War Museum, Duxford.

Figure 4.10: Al Hamra Tower

The *Al Hamra Tower (26)* (figure 4.10) is based on a form generated by floors cut from a vertical tubular square section (SOM, 2008a; Asci & Schwinn, 2008). To achieve a specified total floor area a segment is removed from each floor. The removed segment is rotated by a fixed increment for each floor, the result is a void that spirals up the tubular form. The location of the removed segments was specified in order to achieve the best views while minimising solar heat loads. The result creates warped surfaces which are clad with stone panels. A rationalisation process defined a set of planar unitised panels. Scripted parametric tools were produced to develop a solution where one corner of each panel is shifted into the plane defined by the other three. While this design called for post-rationale, the need to force these panels planar was considered as an aesthetic treatment of surface.

Figure 4.11: Education City

Much of Buro Happold's SMART work is focused on finding flat panel solutions to geometry proposed by architects and the rationalisation of panel systems such as the *Education City (29)* (figure 4.11) (Sharma, 2008; Smith, 2008). This type of task has led to the creation of in-house software called which generates planar and single curvature panels on doubly curved non-uniform rational b-spline surfaces (NURBS). This software is also used to develop equal member length grid solutions.

Figure 4.12: Peek and Cloppenburg

Rationalisation is how DTP (2008) describe their role. They are concerned with finding construction solutions that cover a range of parametrically generated details using straight bars and flat sheets. They work to find the best constructive, structural and functional solution. This process is described as a simplification of the parts. *Peek and Cloppenburg (14)* (figure 4.12) demonstrates a rationalisation process for covering a doubly curved facade proposed by the architects with planar quadrilateral panels. DTP constructed a parametric model of the facade that allowed the horizontal and vertical panel segmentation to be adjusted until the maximum deflection of all panels was less than 6mm.

Pre-rational

Figure 4.13: Free University

Generally the SMG at FP like to avoid post-rational design and implement a pre-rational process (Whitehead & Peters, 2008). *Albion Wharf (8)* and *Free University (7)* (figure 4.13) are described as projects incorporated rational geometry and known construction methods from conceptual design stages. The facade of *Albion Wharf (8)* takes the principles of torodial geometry while the roof incorporates constraints imposed by a sheet metal roofing system. The roof of *Free University (7)* conforms to a series of sheared cone sections which define the geometry of a series of steel trusses which support a double skin of planar panels.

Figure 4.14: St. Mary Axe

The SMG considers pre-rational approaches to be where the geometric system and means of communicating to the contractors are clearly defined early in the design stages. The construction system may not be clearly defined initially but rational geometry that involves planar panels leads to a feasible solution. *St. Mary Axe (5)* is described as pre-rational which meant a parametric model could be developed that allowed sharing the rational geometry, which in turn simplified detailed design, fabrication and construction (Whitehead & Peters, 2008).

Figure 4.15: Bishopsgate Tower

A pre-rational approach is preferred by KPF's Computational Geometry Group (Hesselgren *et al.*, 2007, 2008). The design process for the *Bishopsgate Tower (21)* (figure 4.15) is described as an example of this. The underlying geometry consists of parametrically controlled co-tangent arcs and lines which are extruded to form a series of flat, tapering planes joined at the corners by sheared cones (KPF, 2008). This geometry generates an inner facade comprising of flat planar trapezoids while the outer facade uses standard planar panels that overlap like shingles. Sheared cone and toroidal geometry are applied in a pre-rational way to *CSCEC (23)* and *White Magnolia (24)* (Gun, 2007a,b; Gun & Wallin, 2007).

The design process at FG is in principle concerned with the post-rational, as described above. However, some aspects of this process can be considered pre-rational. Paper and metal sheets are commonly used in Gehry's office to make models. Where these physical materials are not stretched or crumpled, model geometry is constrained to forms that can be clad in sheet materials. This is a pre-rational approach. Shelden (2002) parameterised the principles of modelling with sheets of paper and defined a digital paper surface tool. Surfaces could be manipulated in a three dimensional modelling package and the colour of the surface would indicate if flat sheets could be used as a cladding material.

The capture of simple principles such as the limits of modelling with paper sheets as digital tools can be described as generative geometry. AKT (2008) describe embedded or pre-rational as a generative process where the geometry emerges as a result of understanding the rules that define it. This is contrasted with a post-rational approach where rules are sought that define a specfic form.

4.3.3 Control

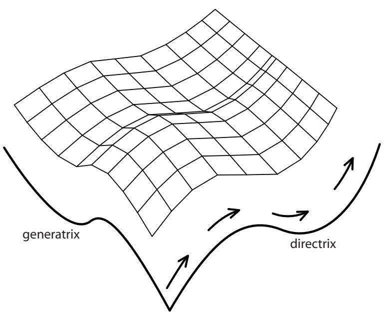


Figure 4.16: Geometric principle of translation surface

Geometric control is one of the primary tasks for the parametric designer. The use of mechanisms to control parametric models is a well documented aspect of commercial parametric practice which is reviewed in this section. Control in parametric modelling can be considered on multiple levels. The lowest level serves to define the fundamental geometry often called the "design surface". Then higher levels of control take this surface as an input together with other parameters in order to define further geometry.

The scaled translation surface described by Glymph (2003) illustrates this control hierarchy. The first level of control lies in the definition of two curves that define a translation surface, the generatrix and the directrix (figure 4.16). These could be changed by moving their control points graphically on screen. A number points are equally spaced along each curve. Translating the set of points on the generatrix to each of the points on the directrix creates a two dimensional array of points that define a mesh of planar quadrilaterals. Logical constraints are embedded in the model so all changes result in true translation surfaces. This mesh then operates as the input for the second level of control, by offsetting from this all construction geometry can be defined. The translation surfaces were associatively modelled in CATIA V5 with the scripting interface KnowledgeWare.

FP's design for the *Smithsonian Courtyard (13)* also uses the principle of a design surface (Peters, 2007; Whitehead & Peters, 2008). The surface (a NURBS surface) is defined by a minimal control polygon. By vertically shifting the nodes of this polygon the surface can be altered. In combination with a structural grid, column position markers and normal offsets this design surface then controls all further construction geometry.

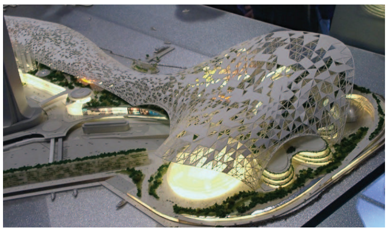


Figure 4.17: Great Canopy

The *Great Canopy (12)* (figure 4.17) also uses the concept of a design surface. The lowest level of control consists of a series of parametrically controlled, planar sectional curves. These define a set of tangential design surface patches (Whitehead & Peters, 2008). Based on the design surfaces, an offset surface defines structural depth, this is controlled with a two-dimensional law curve. The law curve can be considered as a simple b-spline curve defined with a few control points. The curve can be sampled many times at intervals to give an array of gradually changing parameters. From the design surface and offset structural surface a three dimensional grid of nodes is defined setting out a space frame structure. The grid defined on the upper surface then becomes input geometry to control the position of cladding elements. A range of cladding panel types are used, these are located by a further control mechanism which is driven by environmental specialists. Using a two-dimensional plan view panel types could be located graphically, this was then mapped onto the three-dimensional surface and the geometry of the components generated.

Figure 4.18: Acoustic Barrier

A design surface defined with NURBS curves was used by ONL (2008) to define for their 1.5 km design for an *Acoustic Barrier (28)* (figure 4.18) (Biloria *et al.*, 2005, 2006a,b). On the design surface, a point grid is generated based on optimal member sizes. This point grid is then split into a series of smaller parts representing packages of construction documents, each is processed individually to reduce computer processing requirements.

KPF's design for *Nanjing Station (22)* uses a design surface to position cladding components (Gun, 2007a). *Bishopsgate Tower (21)* uses a design surface that is generated by a tapered extrusion of a parametrically controlled ground plan form (Hesselgren *et al.*, 2007, 2008). This surface controls an underlying diagonal grid defining the structure, and is the input for an optimisation routine that minimises gaps between standardised overlapping facade panels. The extent of extruded tapering form is controlled by a law curve which defines a set of parameters controlling the height at which mullions running over the surface terminate, the result is a helical form.

Figure 4.19: Mercedes-Benz Museum

Control of plan form was the first level of control for DTP (2008) in the definition of a parametric model for the *Mercedes-Benz Museum (15)* (figure 4.19). This plan arrangement consisted of circles, tangents and intersection points, these defined planar curves that set out constantly rising spatial curves which describe the building's three-dimensional form.

The AGU (2008) have pioneered the use of an alternative control device. Rather than control a design surface with a polygon or set of sectional curves, an array of polygonal facets are used as a control device. This forms the input to a subdivision algorithm which produces a smoothed surface. This control mechanism has been used in the design process for the *Taichung Opera (20)*.

A further alternative approach to control is discussed by Sharma (2008). The *Scunthorpe Sports Centre (30)* grid shell geometry is defined by a dynamic relaxation process (an iterative method that seeks a minimal energy solution, similar to catenary arch solutions or hanging chain models). The geometry is controlled by assigning different weightings to programmatic requirements beneath the grid shell. These effectively apply different loading conditions across the grid shell which results in an undulating domed form of various heights. BH's SMART group extended existing software for this project after they were approached by an architect who wished to try to use programmatic requirements as a driver for form.

4.3.4 Generate and test

Generating alternatives is recognised in the literature from practice as one of the main tasks for the parametric designer. Changing parametrically defined geometry using well structured control systems makes it possible to generate many options. The task of generating alternatives is directly linked to evaluating or testing these in order to provide some rationale for selection or providing indication of how the design should change. The criteria on which the design are evaluated vary from project to project but can be considered in four main areas, structure, construction, aesthetics and environment. The Generative Geometry group at BH are concerned with evaluation of multiple design alternatives around various criteria (El-Ali, 2008). Gun (2007a) describes how parametric technology allows multiple alternatives to be explored and evaluated. In a design process requiring post-rationalisation, Gun describes how parametric models generate geometry that is assessed on the amount of deviation from the original form.

Gun (2007a) describes how cost and ease of construction are a selection criteria for KPF. The physical modelling of *Nanjing Station (22)* served as a scaled construction process, which was regarded as a test for the full scale procedure. Details and cutting templates for the model construction were generated from the parametric model.

Rapid prototyping is described by Gun (2008) as a way to assess aesthetics and geometric quality of a design. Rapid prototyping is used extensively at FP to assess aesthetic quality. Peters & De Kestelier (2006) describe how the practice has pioneered the use of this technology in architectural design. Peters (2008) considers that rapid prototyping closes the design loop in an otherwise abstract digital design process.

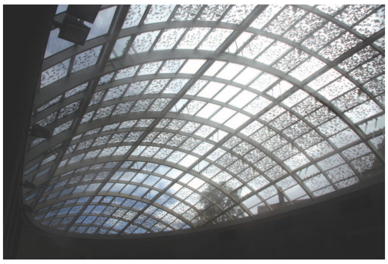


Figure 4.20: Elephant House

The environmental comfort of inhabitants was used as a design selection criteria for the glazed roofs of the *Elephant House (11)* (figure 4.20). The analysis, undertaken by external consultants, determined adequate shading levels for elephants. This was used to define densities of solid patterns (fritting) required on the external face of each of the glass cladding panels. Based on this data the SMG developed a bespoke parametric tool to investigate fritting patterns on the glazing that were inspired by shading provided by trees.

SOM's parametric modelling of the structural system at the base of the *Al Hamra Tower (26)* formed a link with structural analysis, the results of which were used to refine the geometry (SOM, 2008a; Asci & Schwinn, 2008). Structural understanding also informed the development of parametric models and definition of parameters for the *Qatar Petroleum Complex (27)* (SOM, 2008b; Asci & Schwinn, 2008). Initial structural analysis indicated that further parameters were required to adjust the form to achieve better structural performance.

The p.art group at AKT (2008) describe a process where a parametric model was constructed to investigate a branching structure based on multi-performative design criteria. The parametric scripts produced data files for structural analysis. Models were also assessed in terms of geometric arrangements, spatial effects and organisational logic. Based on the results of this combined assessment the model is considered to be a multi-parametric, performing whole. AKT suggest that by establishing models that allow multiple performative factors to be assessed, the process shifts from use of parametric tools as problem solving (rationalisation) to "problem caring, where integral design logics contribute to the coherent employment of novel design method".

Generating geometry and testing it based on multiple criteria is a task undertaken by SOM's integrated parametric modellers. Brugger (2009) describes an urban form massing model that was modelled parametrically in order to maximise day lighting in public areas. Each alternative generated was analysed to check day lighting levels in public areas, ensure floor and vertical transportation areas were sufficient and that egress codes were satisfied.

4.3.5 Share information

The SMG at FP have described the GMS extensively (Whitehead, 2003; Peters, 2008). This way of sharing geometry information is used because it shifts the responsibility for the geometry to the contractor, as they have to reconstruct it. The process of reconstruction is thought to ensure the geometric principles of the design are understood. The GMS works well when working with geometry that is composed of arcs and lines as these can be expressed in simple language. *Smithsonian Courtyard (13)* demonstrates difficulties in using a GMS with NURBS based geometry. For this project contractors needed to employ a geometry specialist (Arnold Walz of DTP) to rebuild the geometry defined by the SMG. Once a contractor has reconstructed the geometry the SMG will then check it against their own by comparing several main setting out points.

Literature originating from FG indicates that parametric modelling generates data that is incorporated into a BIM which is then used as the means of sharing data with all contractors. Lindsey (2002) described the *Barcelona Fish (1)* project and the subsequent establishment of Rick Smith's consultancy, virtualbuildteam (2009) specialising in the management of BIM. This suggests that the practice is dependent on an external consultancy to manage the BIM model. The same consultancy also provides a service to contractors using the same model.

At SOM parametric modellers, integrated into a design team, will develop models and share them with the internal team and external specialists (Brugger, 2009). The models define both design surfaces and structural centre lines which are shared with the design team. When parametric logic is removed, these are then shared as "dead" two and three dimensional data. This is issued in various file formats. Internally this data is used as the basis for traditional architectural drawings which require annotation and further detail to be added. Structural centre-lines are extracted from parametric models and issued to engineers for setting up analytic models. Working in this way the integrated parametic modeller at SOM works closely with manufacturers and fabrication specialists to ensure that the geometric information they issue is transmitted in a usable format. Brugger describes how working closely with manufacturers allows parametric modellers at SOM to resolve geometric issues and undertake construction studies. Internally, the parametric modellers carry out basic environmental analysis and verify detailed geometry for facade systems created by contractor's coordinates with architectural setting-out geometry. More detailed environmental analysis may be undertaken by external specialists who will also be issued non-parametric data extracted from the parametric model.

Operating for project engineers BH, the Generative Geometry group describe the beginning of the design process for Grimshaw Architect's *Fashion and Design Events (31)* Building in Milan (El-Ali, 2008). A multi-disciplinary design workshop was held involving all specialists, and provided an opportunity to agree on a single model workflow and initial parameters.

As an independent consultancy, DTP undertake the task of organising production data for manufacture of parts, nesting cutting patterns, selecting tools, defining tool paths and generating machine code (designtoproduction, 2008). This is a role they have performed for both architects and structural engineering clients. The parametric model they developed for the *Mercedes-Benz Museum (15)* is described as the foundation for all construction documentation. This generated cutting patterns for triangular glass facade panels, steel envelopes of individual columns and planar boards for the form work of doubly curved concrete surfaces.

Figure 4.21: Hungerberg Funicular

Acting for engineers Bollinger Grohmann Schneider on the *Hungerburg Funicular (17)* (figure 4.21) project, DTP produced machine code for polyethylene profiles to connect glass panels to the structure. This was generated from spline curves defining the geometry of each profile and included the machine code for driving a 5 axis CNC router, nesting the parts on boards and automated the production of part lists and identification stickers. The parametric model for the *Peek and Cloppenburg (14)* department store produced detailed plans and sections which formed the construction documentation for the facade contractor. In addition, structural geometry was directly exported to engineering software for structural analysis.

4.3.6 Summary

Tasks were identified in the practical literature in five broad categories. **Translation** involved converting a description of a design idea into a parametric model. **Rationalisation** was described in the literature as a critical part of the translation process. The aim was described as defining geometry with methods that result in,for example, planar panel solutions. This is either applied early (pre-rational) or later (post-rational) in the design process. The point of applying rational depended on the position of parametric designer relative to designer undertaking conceptual design. **Control** of parameters was described as a crucial task which was applied in a hierarchy that organised the model. Descriptions of testing procedures that examined various criteria and required specialist input implied that many alternatives are generated, this indicated a task concerned with both **generate and test**. The need to include specialist analysis of design and produce information for construction identifies the task of **sharing information**.

4.4 Considerations

Considerations were defined in the introduction as the factors that the parametric designer reflects on when undertaking the parametric tasks. The task structure used in the previous section is re-used here to order the descriptions of considerations identified in the literature.

4.4.1 Translation

The parametric translation task is concerned with changing from a non-parametric representation to a parametric model. The starting representation may be a combination of verbal description, hand drawn sketches or traditional CAD drawings. Based on an understanding derived from this initial description, the parametric designer must assemble some idea of what drives the design in terms of the relationships and develop a parametric representation of these. The model development process is recorded as incremental and requiring constant adjustment. The benefit resulting from the effort required to develop these models is in the ability to explore many options and to make changes later in the design process without causing delay to the project.

When translating between design intent and a parametric model, Peters (2007) observes the need for the parametric modeller to understand driving factors behind designs and to know where physical and technical constraints lie. The *Smithsonian Courtyard (13)*, *Elephant House (11)* and *Great Canopy (12)* all demonstrate how algorithms and parametric models develop incrementally, throughout the course of a project they are constantly refined (Peters, 2007, 2008; Whitehead & Peters, 2008).

AKT (2008) and DTP (2008) see the parametric task as being about establishing relationships between the whole building and its parts. They suggest that the process is not concerned with designing the final form but about considering the rules that link the component parts. Similarly, the team working on AKT's *Simplexity (32)* research project (2008) suggest that designers consider the space within which objects are embedded and by which they are informed. Their work demonstrates how stress fields in a volume can be used to define building geometry.

Whitehead & Peters (2008) describe how a programming based approach to generating the geometry of the *Smithsonian Courtyard (13)* enabled them to avoid long chain dependencies that can slow down model updates following a parameter change in parametric software. The code-based model allows modules to be swapped for alternatives to experiment with changes to certain parts of the design while retaining other parts. Using this code based method, changes could be implemented quicker than in an equivalent parametric model.

The benefit of the effort required to establish a parametric model such as the *Smithsonian Courtyard (13)* can be seen as its ability to generate four hundred alternatives in a design period of a few months (Peters, 2007) . Additionally the parametric definition allows design change to be implemented later in the design process. This was also the case with the *Sage (6)* and the *Great Canopy (12)* (Whitehead & Peters, 2008). Whitehead and Peters suggest that when working with rule based methods, designers should consider the way in which depth of exploration is achieved at the cost of breadth. Depth of exploration refers to the ability to produce many variations and high levels of detail based on a design theme or type. For example, alternatives generated for the *Smithsonian Courtyard (13)* were all diagonal grid roofs over a courtyard. Breadth of exploration refers to the ability to assess many design themes or types. The breadth of possible exploration in the SMG's parametric design process is reduced as it is not possible to combine all possible design typologies into a single model. Where the task is very well defined there is no need for breadth in exploration. This was the case for DTP (2008) when working on the *Hungerburg Funicular (17)* project. The need for polyethylene profiles to fix panels to structure was predetermined, the task was about generating the required manufacturing data based on a set of input curves.

In setting up a parametric model it may be possible to reuse a piece of code or script or part of a previously established model. Gun & Wallin (2007) propose that a library be created based on techniques, scripts, programs and models. This library would then be made available to an entire office.

Whitehead (2008) believes that in an architectural practice this is not possible because of different requirements for each project. The individual working on the project is likely to have an architectural background and it is unlikely they will have had formal training in software development. They will have a particular way of building the model and choose a particular type of software. Making their work general and widely reusable would require much effort. Reusable elements would either need to conform to an agreed standard or should be documented. The time required to document in Whitehead's opinion does not justify the effort.

However, for individuals dealing with parametric tasks who do have enough software development knowledge, the development of generic reusable programs or parts of codes is an option. AKT (2008)'s research group is concerned with developing a toolkit of customisable methodologies. The SMART group at Buro Happold have created set of reusable routines as Rhino APIs (Sharma, 2008). These are based around tasks they frequently undertake, such as panelisation of doubly curved surfaces. This set of tools can gradually be extended as the need arises. Work on ZHA's design for the *Hungerburg Funicular (17)* by DTP (2008) demonstrates successful reuse of a method developed for an earlier project. The original project required machine code that defined sectional cuts and included a varying cut angle. Profile paths were defined with sections of a doubly curved surface. The varying cut angle ensured that the section edges followed the surface smoothly. This process was reused to define tool paths to cut profiles that join doubly curved panels back to structure ensuring smooth continuation of surface between neighbouring panels.

4.4.2 Rationalisation

AKT (2008) propose two ways of considering rationalisation, a bottom-up approach where the parts are considered first and a top-down approach where the final form comes first and the focus is on finding parts that will facilitate this. The bottom-up approach is described as generative geometry at the SMG, this is also equivalent to pre-rational (Whitehead & Peters, 2008). Use of pre-rational is recommended once a design concept has stabilised and requires fine tuning, otherwise it may over constrain the design. At FP, arc-based geometry is often used to post-rationalise or pre-rationalise projects (Whitehead, 2003; Peters, 2008). Its use is justified as it allows higher levels of precision and reduces potential problems in manufacture and construction. It also lends itself to simple graphical and text based descriptions used in the GMS. The result of many of the arc-based methods are torus patches and sheared cones. Both are ways of defining planar quadrilateral solutions. Flat panels are preferred over triangular panels for visual and economic reasons; they have fewer members, simpler nodes and generate less material waste.

4.4.3 Control

Peters (2007) describes how a control mechanism can prove the parametric model to be useful or useless. If the model is designed to be used by someone other than the parametric modeller it should be simple and intuitive. An example of this is the minimal control polygons used to define design surfaces for *Great Canopy (12)* and *Smithsonian Courtyard (13)* roof. This simplifies the parameter set required for control and minimises the chances of surface imperfections.

By developing systems that allow design teams to adjust geometry through appropriate control systems the model can accurately capture the dimensions of a specific configuration. The control mechanism described by Glymph *et al.* (2004) allows geometry to be changed based on human intuition. This control strategy is used in combination with a translation surface for rationalising a free form surface. Glymph *et al.* observed that it was possible to achieve satisfactory close matches to the original surface using hand eye coordination to manipulate the model that would be close to solutions found with a computational solver.

4.4.4 Generate and test

The literature places greater emphasis on testing than on the generation of alternatives. This implies that the production of alternatives with parametric models is obvious and simple, but that it is still a necessary task. The ease with which alternatives are produced leads Peters (2007) to propose that the parametric designer consider the need to assess these. In order to make an assessment the designer must understand what criteria are going to be evaluated and what information is needed to do this.

Gun (2007a) describes how the standard tool-set in parametric software can limit the number of possible alternatives. He specifically refers to the parameterisation of surfaces into a UV grid. This, Gun believes, restricts designers to rectilinear arrays of components on design surfaces.

Dritsas & Becker (2007) describe how intuition can reduce the range of possible alternatives. Following this initial reduction, digital optimisation can be used to automate the process of generating, testing and adjusting so a solution can be found. An illustration of this is the facade for Bishops Gate Tower where shingle like cladding is optimised for tight fit.

4.4.5 Share information

Peters (2007) describes how, in order to share information, the parametric model must be able to produce information in many data formats. This can range from information for in-house physical model makers to construct complex models, to centre-line structural models that structural engineers can use as the basis for an analysis model. Other representations define flat pattern drawings of panels (from which manufactures can price work and drive CNC machines), polygon meshes for acoustic and environmental analysis, solid geometry for rapid protoyping and numeric data in text formats for structural analysis.

DTP (2008) are concerned with breaking down whole buildings into parts and producing machine code for those parts. In order to do this they have to consider machine dimensions, range of machine movement and the tools available. It is these considerations that define the parts. Often these parts are unique. In order to share this directly with manufacturers DTP also consider the automation of nesting parts on sheets, generation of unique identifiers and machine code for each part. Without this, DTP claim the cost of using non-standard parts in a building would be prohibitive.

4.4.6 Summary

Tasks were identified in the practical literature in five broad categories the considerations identified for each are summarised here. **Translation** required an understanding of the design intent, anticipation of incremental model development and consideration of rules that link components parts of the building. Contrary opinions were expressed on the use of libraries to initiate models. **Rationalisation** considered as bottom-up or top-down geometric methods. Using pre-rational (bottom-up) methods was recommended only once a design concept is established. Using arc-based geometry was suggested for its simplicity which facilitates high levels of precision when issuing construction information as method statements. **Control** systems should be simple and intuitive allowing hand-eye coordination to define building geometry. **Generate and test** the ease with which alternative designs can be producing suggested careful consideration of the means for assessment. The task of **sharing information** is dependant on ability of the model to produce data in multiple formats.

4.5 Analysis of the position of parametric design in practice

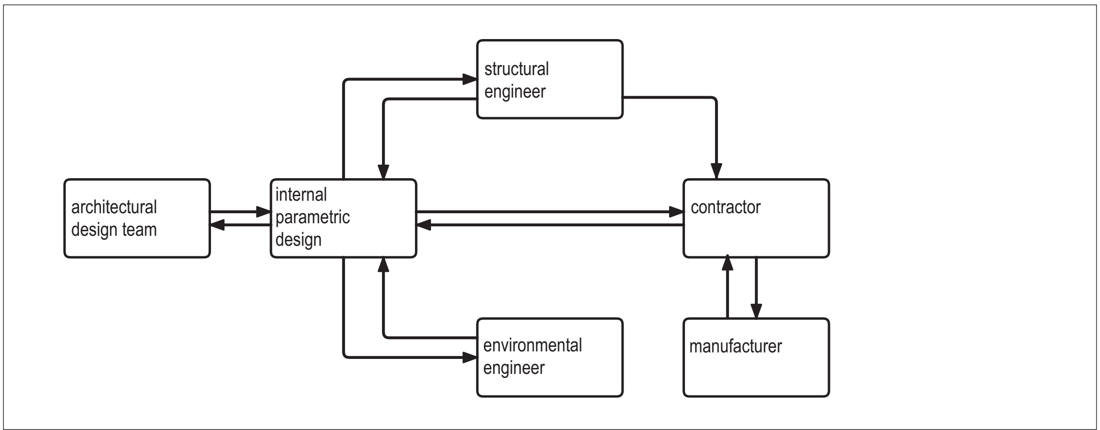


Figure 4.22: **InternalARCH** or **InternalENG** workflow model.

Based on descriptions of the position of the parametric designer in practice, six models of work flow can be defined. These are illustrated with five figures 4.22 - 4.26, each is briefly described and the arguments for and against using them are given. Solid arrows in the diagrams represent direct flow of geometric information (formally agreed in contract) and dashed arrows represent indirect flow of geometric information (informal, not agreed

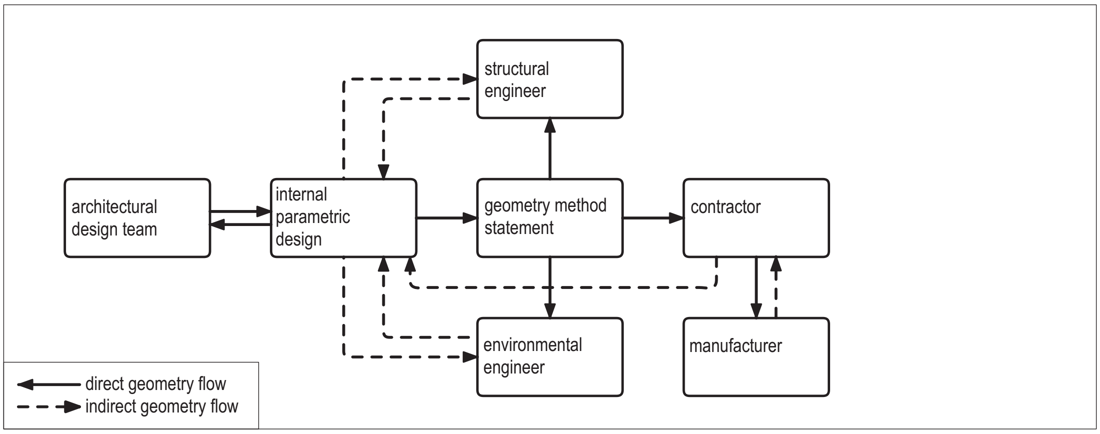


Figure 4.23: **InternalGMS** workflow model.

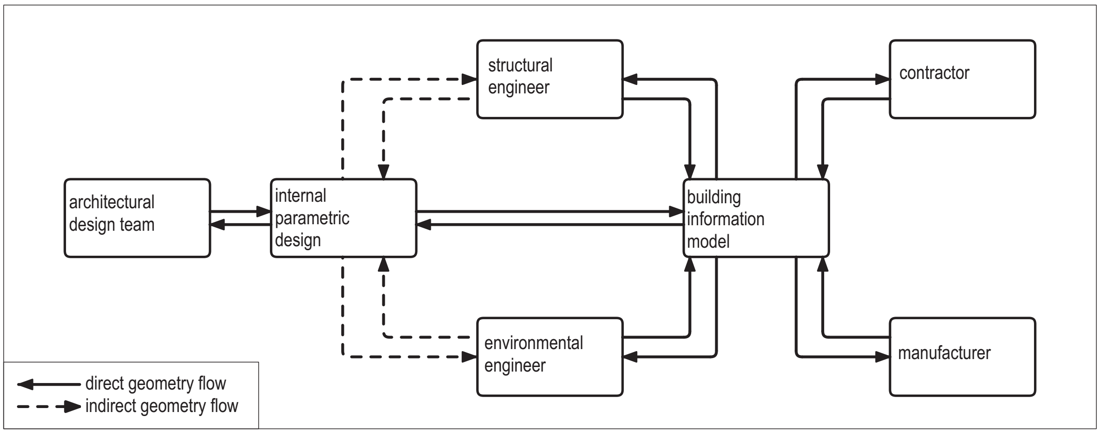


Figure 4.24: **InternalBIM** workflow model.

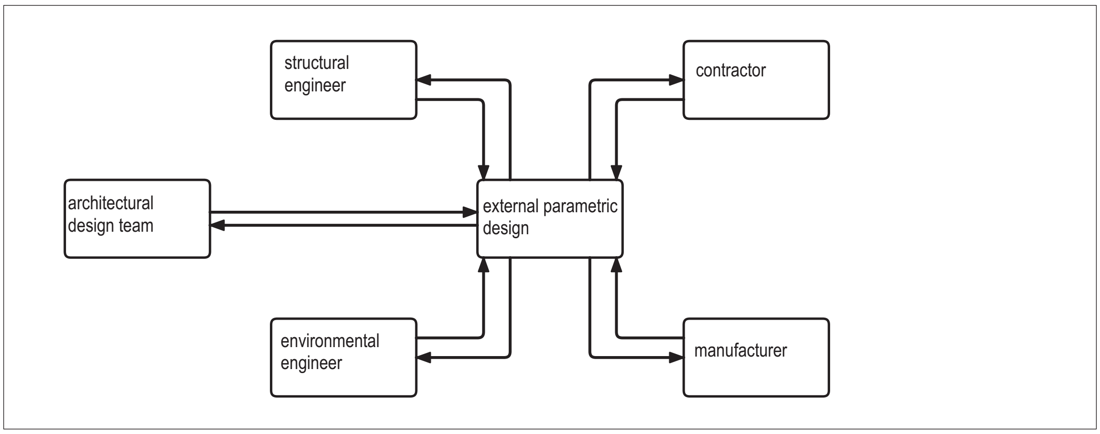


Figure 4.25: **External** workflow model.

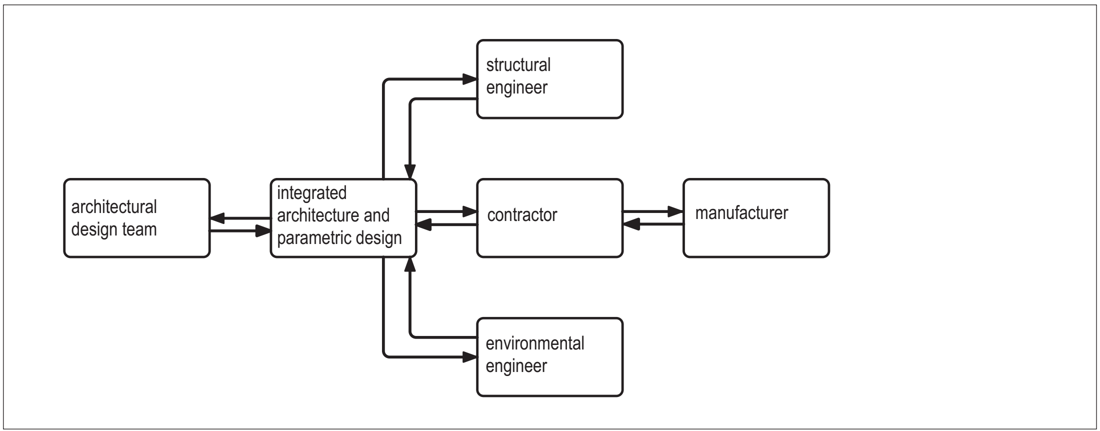


Figure 4.26: **Integrated** workflow model.

in contract). Table 4.1 summarises the workflows by comparing and constrasting the arguments for and against use and identifying the practices where they are implemented.

The first model, **InternalARCH**, (figure 4.22) is a generalised model based on the most commonly reported structure of parametric designers in the literature. Within an architectural practice a small group provide a specialist service to design teams within the same firm. The model corresponds with SOM's DDG and KPF's Computational Design group. In this model parametric design is used to resolve geometric design issues. The parametric designer has the option of working with the architectural design teams from an early stage in the project. In the published material, parametric involvement generally commences once initial design ideas have been developed. The parametric designer frequently performs a role of rationalisation in order to fix problems generated by the design team. The position within the practice is an opportunity to educate design teams on the relative successes, difficulties and failures of geometric approaches used on various projects. Communication between the parametric designer and the architectural design team would be immediate, allowing a high level of resolution of architectural geometry. This makes the InternalARCH model appropriate for projects where architectural geometric control is considered a priority. Parametric designers will share information directly with all specialists. Data is shared in the form of static (non-parametric) CAD files in formats which best suit the recipients. The implications of geometry will reach the architectural design team via the in-house parametric designer.

Figure 4.22 also describes the second model, **InternalENG**. Here the specialist group is based within an engineering firm providing a service to both internal teams and architects from outside the firm. The model corresponds with BH's SMART and Generative Geometry, ARUP's AGU and AKT's p.art. Many of the previous model's characteristics are shared with this model. When working with architectural firms the InternalENG model provides a service for resolving and rationalising geometry in preparation for analysis and later construction. Parametric control within an engineering firm is desirable and beneficial where building geometry can be manipulated to improve structural performance. Geometric implications relating to design analysis will reach the architectural design team via the engineering firm's parametric design group. Architectural design teams are therefore in a position where they can comment on but not directly control geometry. This model is not likely to extend the architectural understanding of construction geometry but a close connection between geometry and structural engineering is achieved.

The next model, **InternalGMS**, (figure 4.23) is based on the descriptions of the SMG at FP. It is a minor extension of the InternalARCH model as it includes a specific mechanism for data sharing, the geometry method statement (GMS). In this model the parametric designer works with design teams within the practice to resolve geometric design issues. The resulting geometry is described in a geometry method statement, this is shared with external specialists who are required to rebuild the geometry. This method of information sharing gives the parametric designer indirect contact with structural and environmental engineers, contractors and manufacturers. Rebuilding the geometry is a repetition of work, but is intended to ensure others understand the geometry. It has been shown to work well with arc-based geometries that can be simply described in words and diagrams. For more complex forms, specialist skills may be required for reconstruction, which could constrain project geometry.

The third model **InternalBIM** (figure 4.24) is based on a work flow organised around a Building Information Model (BIM). It is also a minor extension of the InternalARCH and InternalENG models. In this model the parametric modeller and other specialists add and extract information from and upload information to the BIM. The InternalBIM model corresponds with to SOM's DDG (where BIM are used) and by implication FG[2]. In this model the parametric designer is responsible for establishing the principle geometry of the project. Given a file-sharing system that archives, updates and controls editing rights, parametric control of the principle geometry could be retained throughout the project. Potentially this

[2]Evidence of an internal parametric consultancy is not explicit in the literature on FG but use of BIM is.

would make significant changes possible at later stages of design. Information is shared through this central model so the architectural design team have indirect contact with the specialist groups. There is no evidence in the literature of parametric control being retained within the BIM although the software allows this. Instead, parametric models generate geometry that is incorporated into the BIM in a static form. Each specialist will extract the information they require to build a model of their respective part of the building. This is then uploaded to the BIM and the architectural team take responsibility for checking the combined geometry. Checking and management of information may become the responsibility of a model manager who could be external to the process or part of one of the teams involved.

The next model, **External** (figure 4.25) is based on descriptions in the literature where parametric work is undertaken by an external consultancy firm. In this model the parametric designer has immediate contact and directly provides and shares information with external specialists (structural and environmental engineers, contractors and manufacturers). Involvement in projects occurs at the detailed design stage. Subsequently, work is concerned with rationalisation of problems posed by architects and organising production and construction information. The separation between the parametric design work and the design team could present problems in terms of translating design intent, since each project will require an understanding of the working methods and thoughts of a new group of designers. The separation of architectural and parametic design will make it difficult for parametric knowledge to filter into the work of the architects. Separation will also mean that the parametric work remains beyond the scope of traditional architectural activities. The model corresponds with the working methods of designtoproduction and Burry.

The final model, **Integral** (figure 4.26) is based around the parametric design role described at SOM where parametric designers are incorporated into the design team. Rather than act as a consultant to the architectural design team they work alongside as a single team. This position gives opportunities for direct contact with and feedback from specialist consultants and collaboration with the architectural design team. The model makes parametric design available from the outset of the design process to provide early investigations into geometry and basic analysis. With small changes the Integral model could work in a similar way to the InternalBIM model. The Integral model is dependant on individuals who are concerned with the complete design of the building not just the specialised resolution of geometric or fabrication issues. The role of parametric design in this model is to ensure the best options are developed at all stages of the project.

4.6 Analysis of tasks and considerations

4.6.1 Practical confirmation of theoretical descriptions

This section identifies the way in which the tasks and considerations identified in this chapter provide evidence and examples for the tasks and descriptions identified in the theoretical literature. In order to clearly distinguish between the descriptions of the parametric role developed in this chapter and those developed previously, two terms are used. Practical literature, refers to work reviewed in this chapter and material reviewed in the previous chapter is referred to as theoretical literature.

Create model

Both sources of literature describe a create model task, but the sub-tasks idenitfied are significantly different. In the theoretical literature, the parametric task began with development of a problem description. In the practical literature there is no mention of this early stage in the parametric process. The parametric task in practice is generally not concerned with developing design ideas early in the project. The major concern is resolving geometry and fabrication issues of a predetermined object. There is an assumption that the right design has already been found. It is given to the parametric designers as a sketch, sketch model, CAD model or drawing together with verbal description. The first task in the practical literature is to translate this into a parametric model. When developing this model the practical literature emphasises that when constructing a model the parametric designer should consider rules and relationships rather than the completed geometry. This is a reiteration of a consideration identified in the theoretical literature.

In the theoretical literature, opinion was split between implementation of parametric modelling at conceptual or post-conceptual design stages. Early implementation was identified as an opportunity in the theoretical literature as it can assist with the development of problem descriptions. Later implementation was argued for on the basis that the

Model and related practices	Arguments for use	Arguments against use
InternalARCH		
SOM's DDG, KPF's Computational Geometry	Resolution of architectural geometry issues	
	Can be used for early stage design tasks.	Literature suggests early stage use is likely to be over looked.
	Educate practice in geometric issues.	
	Share information direct with specialists.	Contractual systems limit architecturally generated data to design intent only.
	When high level of architectural control is required.	
InternalENG		
Arups' AGU, BH's SMART, BH's Generative Geometry, AKT's p.art	Where structural geometry is fundamental to project.	Little architectural control of geometry.
	Resolution of geometry direct communication with sub contractors and specialists.	Geometric implications communicated via intermediary to architects.
	Production of information for construction.	Parametric design removed from architectural scope of work.
InternalGMS		
FP's SMG	Resolution of geometry where text based description is possible (arc-based).	Complicated for more complex geometry.
	Rebuilding ensures sub-contractors understand geometry.	Rebuilding geometry is repetition of work.
	Can be used for early stage design tasks.	Literature suggests early stage use is likely to be over looked.
		Feedback from sub-contractors is indirect following reconstruction.
		Reconstruction by sub-contractors must be checked.
InternalBIM		
SOM's DDG, FG	Late changes to design possible.	Information manager maybe required.
	Centralised set of shared data.	Feedback to architectural design team is via BIM and then parametric design group.
External		
designtoproduction, Mark Burry	Direct data sharing with all sub-contractors and specialists.	Parametric design removed from architectural scope.
	Rationalisation and geometric resolution for construction.	Architectural design separted from geometric implications.
Integral		
SOM	Early application of parametric tools.	
	Direct contact with sub-contractors and specialists.	Contractual systems limit architecturally generated data to design intent.

Table 4.1: Comparison of workflow models.

hierarchical structure of a parametric model could restrict the breadth of conceptual exploration. The practical literature demonstrates how parametric tasks are undertaken after the conceptual design stage is complete. This provides evidence of implementation of parametric design at later design stages but overlooks the possibility of application to early stage design tasks.

In the theoretical literature, use of libraries was described as a means of initiating the design process. The practical literature suggests that a library of methods may be considered applicable at later design stages. However, opinions in the practical literature on the notion of creating libraries for reuse of technique are split. Parametric designers operating in internal consultancies within engineering practices are concerned with developing reusable tools and software. Whereas the director of Foster and Partner's SMG has informally described the possibility of library development as problematic. In developing and using such a library, careful judgement is required so the stored techniques are generic enough to be reusable, and that over dependency on the same methods does not develop.

Control

Fragmentation is explicitly described in the theoretical literature as a means of approaching difficult problems and organising a composition of a parametric model. In practice a fragmented control mechanism potentially enables design team members who do not have parametric skills to take responsibility for part of the control system. The practical literature demonstrates how part of the input to a fragmented control mechanism can include static CAD geometry files, which can be defined by any member of an architectural design team.

The approach to control described in the practical literature is about developing hierarchies. A control hierarchy breaks the parametric modelling task into more manageable pieces. This process of fragmentation, described in the practical literature, splits the model into logical parts. This can avoid long chain dependencies associated with parametric software. The fragmenting of control systems also means that models can become modularised and can be shared amongst a team of parametric designers. For this to work all team members need to communicate the nature of interface between modules.

In the theoretical literature, parametric control objects were described as an opportunity to efficiently evaluate sets of parameters. The law curve described in the practical literature is a control object that can generate a list of parameters based on a minimal set of control points. A design surface was described as a means for actually specifying geometry rather than acting as a device to produce sets of parameters.

Generate and Test

In the theoretical literature the generation of alternatives is described as exploration. It was suggested that the parametric designer needed to be aware of the abstract concept of the problem space and that exploring this space was about constructing paths into it. Additionally, a series of "amplifiers" for assisting the exploration were proposed. In the practical literature there is no hard evidence of awareness of the problem space or that this helps when exploring a design parametrically. Some evidence of the "amplifiers" suggested in the theoretical literature can be identified in practice. These can be seen in the structure of software used for parametric design. The use of software that reduces the formal complexity of defining parametric models is an example of use of informal representations. Those applications offer interfaces for designers to work with scripts or develop APIs, described in the theoretical literature as codification. Some software such as GenerativeComponents provide the means for recording the design configurations explored so the designer can return to an early state or replay a towards a later one.

In the theoretical literature, the task preceding the generation of alternatives is finding appropriate initial values. In the practical literature initial parameter values are determined based on an understanding of the constraints of the problem. This understanding is extracted from static CAD files, sketches, sketch models and verbal descriptions. Interpretation to establish initial parameters is part of the translation task.

A link between design assessment and model revision is described in the theoretical literature and this is emphasised by descriptions of iterative design methods. In practice, basic assessment of design is undertaken by the parametric designer but more sophisticated assessment is handled by specialists. Specialist assessment involves studies of building performance in terms of structure, environment and acoustics amongst others. Within an architectural practice these criteria may be examined on a more basic level together with assessment of construction logic and aesthetics. Iteration in the practical literature receives less attention but it is implied by descriptions of geometric change following analysis results. Each type of assessment requires an alternative representation of the model which is shared with a particular specialist who undertakes the analysis. Feedback from analysis then indicates ways in which the model can be changed.

Knowledge of the structure of the parametric model was an important consideration in the theoretical literature. With this knowledge the parametric designer would know how to adjust parameters to affect a specific geometric change. If further parameters are required or the model structure needs reorganising, the parametric designer would be able to undertake this. The extent of changes to model structure described in the practical literature is small. Parameters are added and control mechanisms adjusted but the broader structure of the model remains unchanged. These small changes are described as happening incrementally as the design progresses.

Sharing information

Sharing data is described as an opportunity in the theoretical literature and the practical literature validates this. Sharing information forms an essential part of the parametric design task. In practice some design assessment is undertaken by specialists. Each form of assessment requires a particular format of design data and the parametric model is required to produce multiple representations. The theoretical literature suggests that the parametric designer considers the type of data required for assessment at an early stage in the model construction. In the theoretical literature the use of multiple representations was considered important for generating new design ideas.

Information is shared in different ways, this is dependant on the position of the parametric designer relative to the design team. Static CAD files, CAD files combined into BIM and geometry method statements are described in the practical literature as methods for sharing data. No sharing methods were identified that involved retaining parametric control in the shared data. Contractual arrangements that define work flow determine the ability to directly or indirectly share data. Work flow models identified in the practical literature are illustrated in figures 4.22 - 4.26.

4.6.2 Practical additions to theoretical descriptions

This section identifies tasks described in the practical literature that were not described in the theoretical literature.

Rationalisation

Rationalisation is a new task that the practical literature introduces as part of the role of parametric designer. Two approaches to rationalisation are identified. It is seen as a solution to a problem generated by ideas that are detached from budget, construction and fabrication constraints, a problem that shouldn't exist. Alternatively it is accepted as a necessary task that seeks to preserve design intent while aiming to satisfy budget constraints. Parametric designers in an internal consultancy within an architectural practice are in a position to avoid post-rationalisation as they can work directly with design teams, although this does not necessarily happen. Integrated parametric designers are responsible for avoiding post-rationalisation as they always work directly with architectural design teams.

Parametric designers operating as independent external consultants or within an engineering practice become involved with projects at later stages. Consequently their task is concerned with post-rationalisation. The opportunity to implement more rational solutions earlier in the process is therefore missed. The approach of these parametric designers is to seek efficiency gains in terms of work flow, structure and fabrication based on geometry defined by the architect. They are primarily concerned with rationalising geometry and automating the generation of analysis data files. For groups providing a parametric service to architectural design teams, re-use of methods is a particularly important factor in their tasks.

Taxonomy of design representations

Based on descriptions of multiple data formats that are required for specialist assessment in practice, a taxonomy of design evaluation representations can be identified.

- Construction logic (physical models from flat sheet laser cutting, rapid prototype data)
- Aesthetics (from physical models)

- Aesthetics (visualisation from three-dimensional models for rendering)
- Structural performance (analysis based on structural centre lines, polygon meshes, analysis data file definition)
- Thermal performance (analysis based on polygon meshes)
- Acoustic performance (analysis based on polygon meshes)
- Costing (panel layout and material quantities for pricing)

Assessment

The practical literature identified opportunities for parametric methods to enhance design assessment and to develop models which were concerned with geometry beyond the form of buildings. Binding analysis results directly to building geometry both in physical models and on screen is an opportunity for more direct assessment of the performance of a design and the related geometry. Parameterised metrics of human perception have been used to examine the quality of view based on a series of measures in auditoria. Parametric models representing a volume of material, the loading on it, and its supports, have been used to dynamically manipulate stress fields in order to define a form.

4.6.3 Unrealised theoretical descriptions

This section identifies aspects of the theoretical literature that have not been fully realised in descriptions from the practical literature. The theoretical literature suggested parametric design could help form a better understanding of problems, assisting in design exploration and sharing data.

Understanding the problem

Using parametric design to form a better understanding of the problem is unrealised. The practical literature demonstrates how when using parametric technology in a detail design phase designers are forced to consider geometry and how this relates to construction method and building performance. This essentially forces a more detailed and therefore better understanding of the process of resolving the geometric and construction issues of a particular object. In part this validates the theoretical opportunity. In practice the use of parametric technology to explore the problem in early design stages is overlooked.

Assist exploration

Using parametric design to assist in exploration is partly fulfilled. Detailed design stages are described in the practical literature as benefiting from parameterisation. Small changes, to generate a new design alternative that improves on the previous design can be made. This is essentially exploring a limited problem space. Therefore the exploration is of a narrow field, defined by the parametric model, but involves a high level of detail. If parametric methods are applied earlier in the design process it may be possible to achieve greater breadth of design exploration.

Share information

Sharing information and assessing designs forms a core component to the role of the parametric designer in practice. The theoretical literature suggested sharing information using a parametric definition. In the practical literature there are no descriptions of type of data sharing. This would allow a more rapid sharing of design change and given the correct editing rights different specialist in the design team could change aspects within their responsibility.

Incorporating intuition

Intuition forms an important component in the design theory that the theoretical literature was based on. Intuition was referred to as heuristics, methods based on rules of thumb or experience, and used to establish a design idea by defining an area of interest. This immediately reduces the range of possible solutions. Few aspects of the practical literature indicate that intuition continues to be a way of reducing the range of possible alternatives in parametric design.

4.7 Summary

The findings from this chapter are illustrated in figure 4.27, this is a development of the figure first presented at the end of the previous chapter. Here, figure 4.27 shows where the practical literature confirms the tasks identified in the theoretical literature. Further contributions are also represented along with a reference to the particular practice or project where they were observed. Numbers used in the diagram to reference projects and acronyms for practices correspond with those used in figure 4.1 and in the glossary.

The practical literature confirms the create model task and adds the further sub-tasks; translation, rationalisation and control. The design investigation task in practice was observed to be concerned with generating and testing design in terms performance, construction cost and logic. Construction documentation was identified as a further task in the practical literature and was concerned with producing representations for sharing, combining into shared models or developing descriptions of geometric methods. Some contrasting opinions were identified relating to the use of libraries to establish parametric models and critique of the hierarchical structure of parametric model expressed in the previous chapter was reiterated.

The next part of this thesis involves case studies where the author participates in parametric design tasks in practice as a parametric designer. The purpose of this is to provide a view of practice that is not captured in literature. The descriptions in the literature present completed processes, which benefit from hindsight and illustrate error free sets of activities. In contrast to this the intention of the case studies is to capture the design process as it happens, including mistakes and fruitless directions. The aim is to continue to develop the understanding of the role of the parametric designer by adding to the existing descriptions of tasks and considerations.

Analysis of the reviewed literature suggests specific areas that the case studies should focus on. The first area is where tasks and sub-task have been proposed in the theoretical literature but have not been fully achieved in practice. The second is where opinion in the literature is split. The third area for case study focus is practical aspects described in both the theoretical and practical literature that have not received detailed descriptions or practical examples.

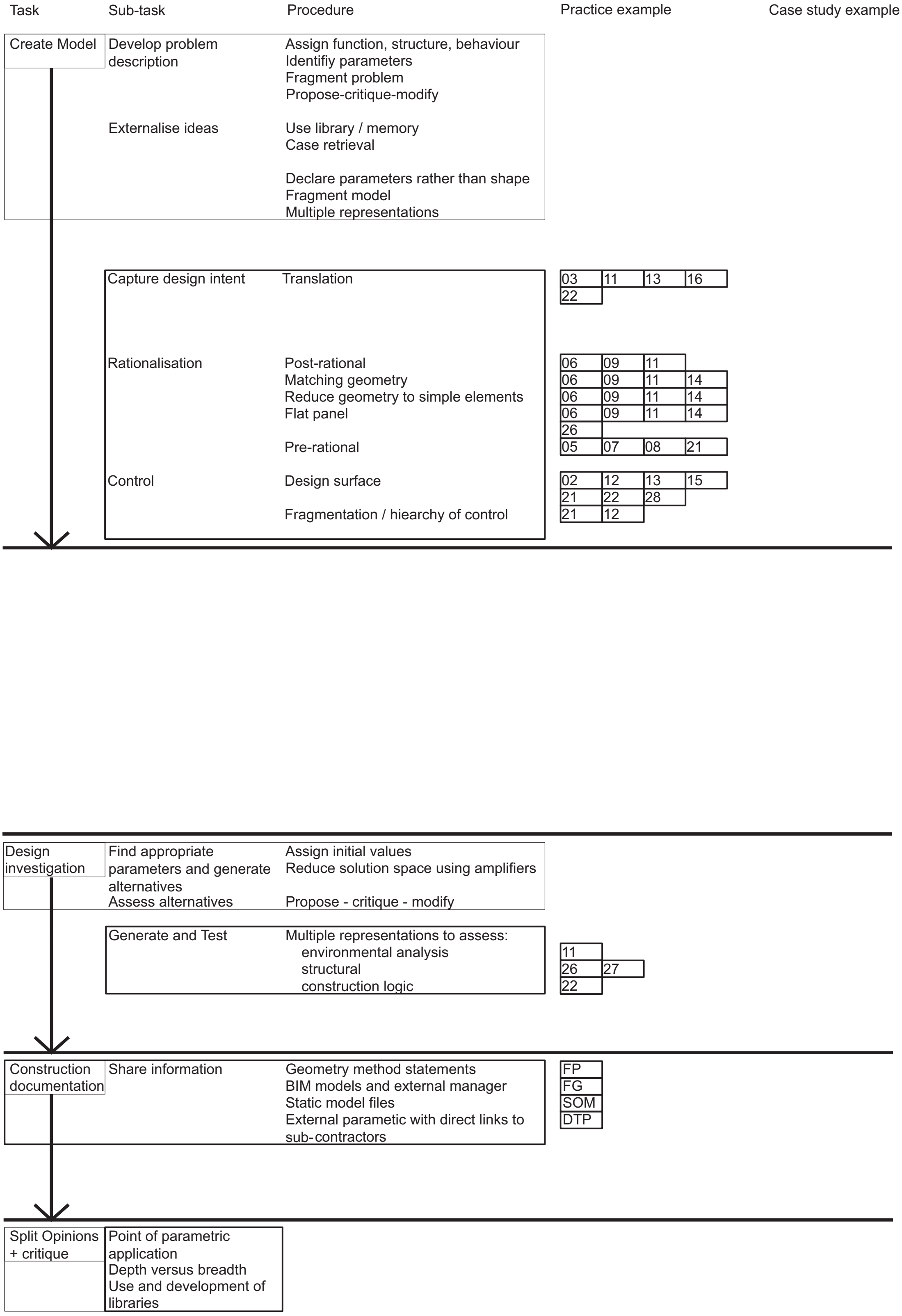


Figure 4.27: Task structure.

4.7.1 Unfulfilled theoretical proposals

The theoretical literature proposes that using parametric design at early design stages can establish a better understanding of the problem or assists with development of problem description. Secondly the theoretical literature suggests possibilities for sharing parametric definitions within the design team. Lastly the role of design intuition forms an important part of the theoretical literature which suggests that it can be amplified by parametric design.

4.7.2 Split opinions and critique

Split opinions exist over the point of implementation of parametric design. This aligns with the need for further examination of how parametric design can assist the development of design description in early design phases. Contradictory views are described surrounding the re-use of parametric techniques, models and scripts. Parametric models were criticised for their rigid hierarchical structures that can facilitate depth of exploration at the cost of breadth.

4.7.3 Expansion of tasks, sub-tasks and procedure descriptions

Further descriptions and examples are sought of capture of design intent, and the fragmentation of models and control mechanisms. Capture of design intent involves the extraction of initial parameters, constraints and design intent from descriptions that are not parametric. The use of fragmentation plays an important role in making tasks more manageable. It has been implied as being part of breaking model structures into modularised parts. The development of multiple user control systems, which were alluded to in the theoretical literature is a further area for focus.

Introduction to the case studies

The previous chapter identified a series of key areas that the case studies should seek to examine in order to expand the understanding of the role of the parametric designer. Identification of these areas was the result of a review of literature which included design theory, parametric design theory and published material from practice. Comparison and analysis of this material identified the following areas for further study:

1. **Unfulfilled theoretical proposals.** Where theoretical descriptions of parametric possibilities were not realised in practice.
2. **Split opinions and critique.** Where contradictory views were expressed in the literature and practical examples did not provide sufficient evidence to further the debate.
3. **Expansion of tasks, sub-tasks and procedure descriptions.** Where parametric tasks and considerations could be identified in the literature but practical examples did not provide a full description or examination. The practical application of these tasks and considerations was therefore not validated.

By focusing on these key areas, the case studies will continue to develop the understanding of the role of the parametric designer. Practical literature will tend towards polished descriptions of projects, whereas the case studies will allow irrational and rougher working practises to be discovered, adding further to the understanding of the role of the parametric designer.

Each case study chapter is structured in two parts, a brief description of the design process followed by an analysis of the development of the process. The description of the design process identifies the primary functions of the implemented system. Where possible, illustrations and diagrams are provided to minimise text-based descriptions. The intention is not to dwell on specific geometric details of the project but to use the experience to discover and examine further aspects of the role that either have not been revealed or not presented in great detail in the literature review. Analysis of the design process aims to reveal further details that support and contribute to the areas identified at the end of the previous chapter.

Chapter 5

Lansdowne Road Stadium

5.1 Introduction

This chapter reviews the parametric design work undertaken by the author for Lansdowne Road Stadium (LRS) (LRS has subsequently been renamed AVIVA Stadium, but will be referred to as LRS herein). More detailed descriptions of this project have been published by Shepherd & Hudson (2007), its relevance to aspects of design theory is discussed at length by Hudson (2008a,b, 2007). The development of the cladding solution is dealt with by Hudson (2008c, 2009). Various general descriptions of the project have been published in the architectural press, see Kucharek (2008) and HOK (2008).

The content of these publications illustrate how this case study contributes to the understanding of the role of the parametric designer. The project provides an opportunity to examine several of the key areas for further study identified in the first part of this thesis. These include:

- Early design stage application of parametric methods to develop a problem description, which contributes towards the discussion regarding the point at which parametric design is applied.
- The role of the ”propose, critique and modify” model of design in later stages of design.

- Use of a parametric definition shared between architects and engineers.

The project also provides further practical examples of parametric tasks already identified, but not fully described or illustrated by the practical literature. These include translation, fragmentation of control system, fragmentation of problem, use of multiple representations and defining initial parameters. Lastly the chapter describes how the LRS case study defines a new parametric task that crosses traditional contract boundaries by involving an architectural parametric designer in the detail design phase of the project.

5.1.1 Background

Parametric modelling of this project began in March 2006 when the author began working as a consultant to the project architects HOK Sport Architecture (HOK are now known as Populous (2009) but are referred to herein as HOK). Parametric modelling was directed by HOK's LRS facade and roof design team. Planning permission for the project had been granted prior to the involvement of parametric modelling. The concept design phase had indicated to HOK that manual adjustment of geometry during the design development was unfeasible. Changes to refine the stadium geometry were anticipated during the design development and detail design phases of the project. The implications of geometric change for construction documentation on such a large project prompted the design team to seek a more efficient form of modelling. HOK use Microstation (BentleySystems, 2008) as their CAD platform, Bentley System's GenerativeComponents (GC) was therefore an obvious choice as the parametric platform for the project. Before this point parametric design tools had not been used within HOK. The design development phase of LRS presented an opportunity to trial parametric capabilities within the practice. The project structural engineers were *Buro Happold* (BH) and the application of parametric modelling was seen by them as an opportunity to develop an innovative integrated approach. This was undertaken in terms of information shared between Architects and Engineers. At the time of writing the stadium is under construction and due for completion in 2010.

5.1.2 Context

The stadium site was highly constrained, with tight boundaries to the north and south formed by low rise residential buildings (figure 5.1 left). These dictated rights-to-light planning restrictions limiting the overall height of the stadium to 50m and chamfering the possible development volume at the north end. Expansion to the west was limited by the retained rail link and to the east by the grounds of a local rugby club. Inside the stadium resisting these external forces was a requirement for a seating capacity of 50,000. Exhaustive daylight studies defined the position of the inner roof edge to provide adequate natural light to ensure a healthy grass pitch growth. The design submitted for planning approval proposed a form resulting from a combination of pressures from all these constraints (figure 5.1 right). Although not initiated in a parametric way, the underlying geometric considerations for the early design were rule driven.

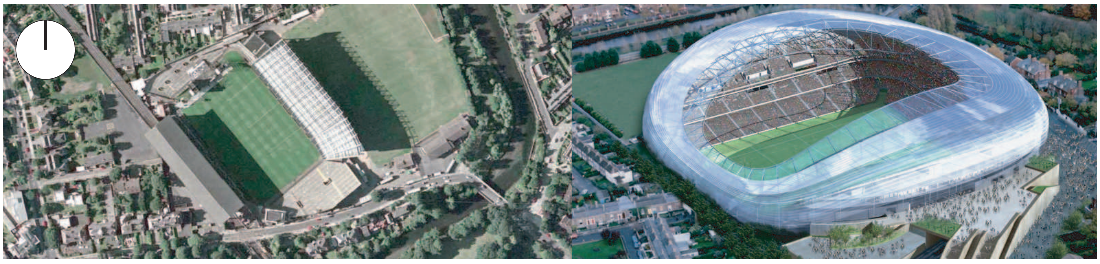


Figure 5.1: Right: LRS Site. Left: Proposed stadium.

5.2 Overview of the completed parametric model

The parametric process can be described in four distinct phases (figure 5.2). At the root of the process is the geometric definition of the envelope geometry, which was the responsibility of the architects. This formed the basis of the design of the structural system and the facade. Structural design was undertaken by BH and the facade design remained the responsibility of HOK. Construction documentation of the facade was developed parametrically. Facade information was issued to specialist cladding designers, William Cox and Clad Engineering (WC+CE) who developed detailed design for manufacture. The detail design phase was supported with a series of parametric models developed by the author on behalf of HOK. Detail design proposals by WC+CE were checked by integrating them into the initial parametric models.

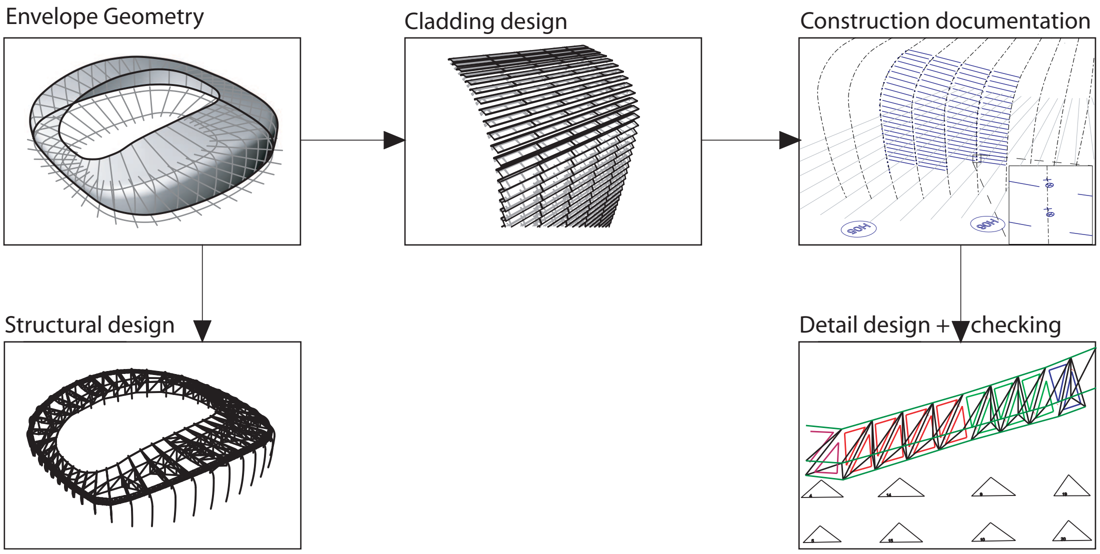


Figure 5.2: Process structure

5.2.1 Envelope geometry

Architectural modelling of the stadium envelope geometry consisted of three components; numerical parameters, static geometry files and a GC script file. The parameters, or numeric data, were stored in an Excel spreadsheet, and were read into GC as the script file was executed. Static geometry was also referenced in from CAD files. From this initial data and rules defined in the script file, a graphical control system was constructed which defined the configuration of the stadium geometry.

The first step in the geometry construction sequence was to import the CAD file that defined a radial grid that corresponded with structure of the roof (figure 5.3 1). Eight parametrically controlled tangential arcs defined the footprint of the stadium (figure 5.3 2). The same system was used to define the inner edge of the roof (figure 5.3 3). The intersection of the footprint and the radial grid defined the origin of each sectional curve (figure 5.3 4). Each section comprised of two arcs and a straight line all meeting at tangents (figure 5.3 5). Vertical coordinates for each section were defined with three planar control curves (figure 5.3 6). Horizontal coordinates were determined by the intersection of the radial grid and the footprint curve and the inner roof edge curve. Once each sectional curve was constructed a surface was lofted through the entire array (figure 5.3 7 and 8). When the radial grid was redefined with more grid-lines the continuous control curves allowed more sectional curves to be defined (figure 5.3 9).

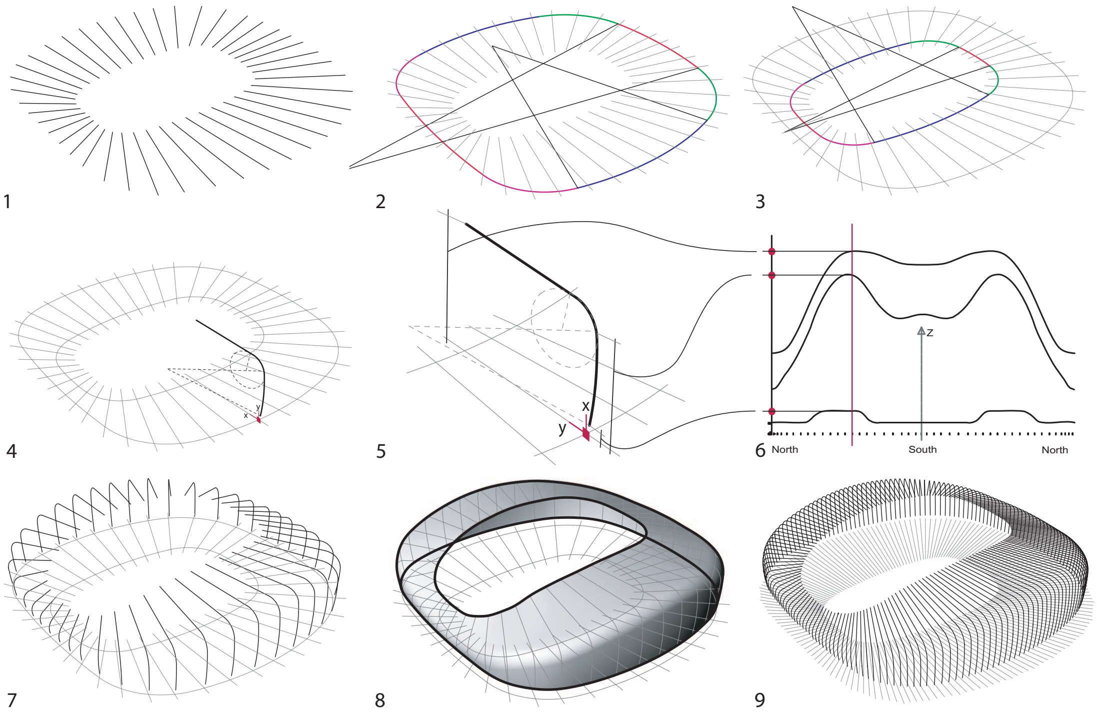


Figure 5.3: Geometric and control method.

Built into the model were two mechanisms for extracting two-dimensional drawing data. Using the lofted surface and an orthogonal grid that corresponded to the seating bowl, vertical sections could be extracted. Floor levels, defined in the spreadsheet, controlled horizontal planes which when intersected with the envelope surface defined curves. When offset inwards these defined the extents of floor slabs. Once extracted these sections and plans were saved in individual drawing files which could be referenced into the HOK design team's set of two-dimensional drawings.

5.2.2 Structural design

HOK wished to retain full control of the external geometry while BH would design the structural system to support this. A hypothetical boundary surface was discussed before any parametric modelling had been undertaken. This separated the remit of engineering responsibility from that of the architect. The envelope geometry defined the interface and it was controlled by HOK and then issued to BH. This allowed the external geometry to be manipulated, changes issued as a set of updated parameters, and then the structural geometry and corresponding structural analysis would automatically update.

The parametric envelope geometry was defined with sections arranged radially, these were the starting point for the parametric structural model. The radial section curves represented the interface between the architectural and structural design. Using the sight lines from the last row of seating, bending moments and transportation constraints, a series of geometric rules were defined. These rules generated a centre line model of structural members (figure 5.4). An export routine was written in C#, this was embedded in GenerativeComponents. The routine calculated initial member sizes and loading, reformatted the geometric definition and wrote a data file which was then used for structural analysis. A full description of the structural design process is beyond the scope of this thesis, but is discussed in detail in Shepherd & Hudson (2007).

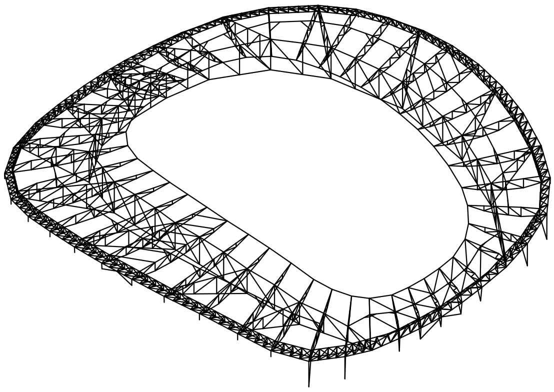


Figure 5.4: Structural geometry.

5.2.3 Cladding design

The starting point for the cladding design was also the radial array of sections that define the envelope geometry. Intermediate sections were required to define mullions which supported the cladding between structural bays. Each structural bay was divide by three, four or five depending on the bay size. The cladding system was designed as a rain screen consisting of inter-locking louvres (figure 5.5). Panels were planar and made from folded polycarbonate sheets, all panels used the same profile but varied in length. A lateral axis of rotation allowed panels to be fixed in a range of positions between open and closed (figure

5.6). This allowed sections of the facade to be open to allow air intake and exhaust for air handling units positioned behind the facade. The polycarbonate panel was fixed onto an axle along its own lateral axis. This axle was supported at either end by a bracket which was connected to a mullion. The brackets had two axes of rotation, the angles for each were defined by the positions of neighbouring panels (figures 5.7 and 5.8). Parametric modelling of the entire facade provided a means for checking that HOK's proposed cladding system would work correctly all round the stadium and this ensured a high level of architectural control of the system. The parametric model was also used to produce geometry files for three-dimensional visualisation both in computer generated graphics (figure 5.18) and physical models (figure 5.9).

Figure 5.5: Proposed facade, elevation and detail.

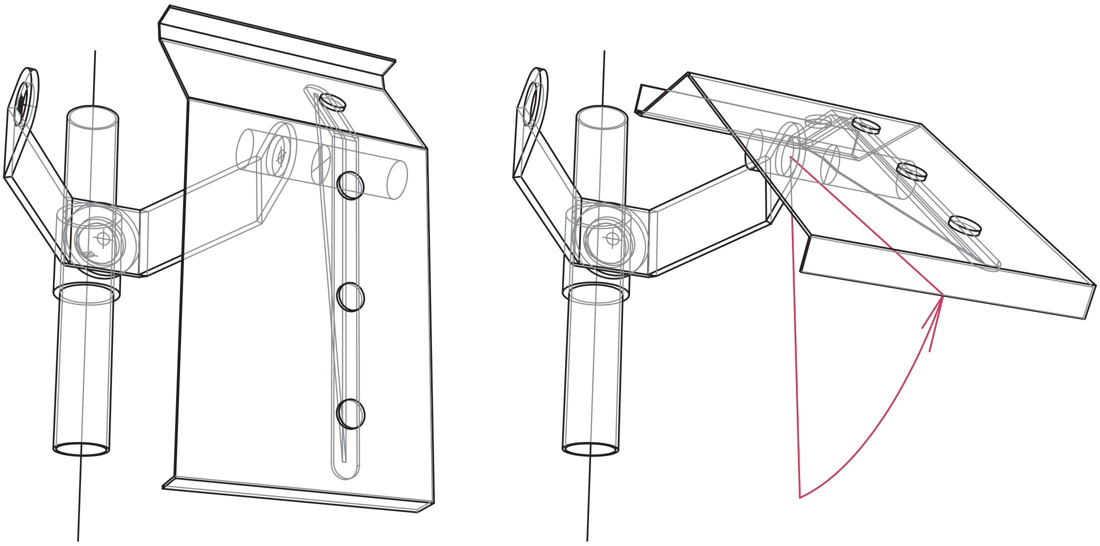


Figure 5.6: Panel rotation axis.

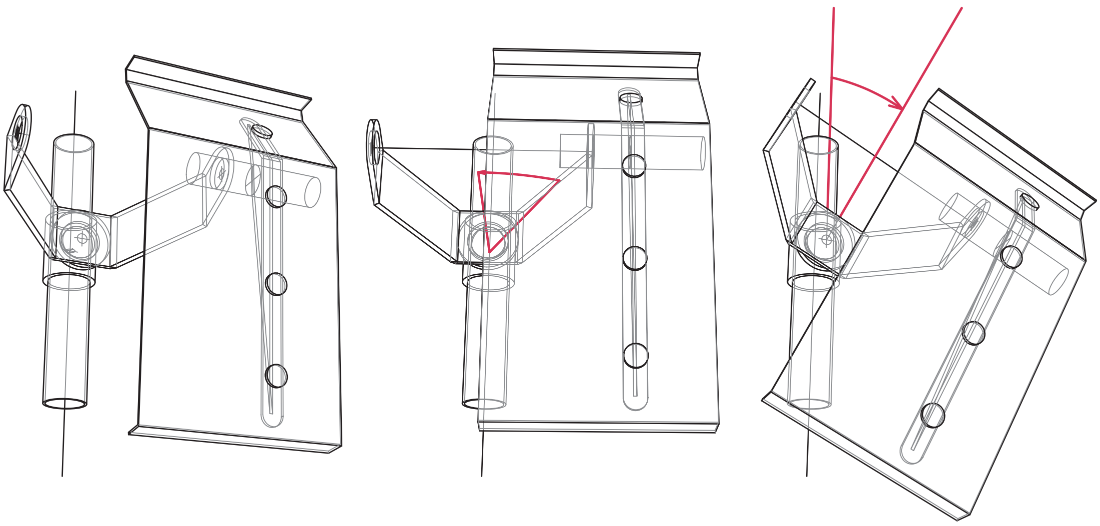


Figure 5.7: Bracket rotation detail.

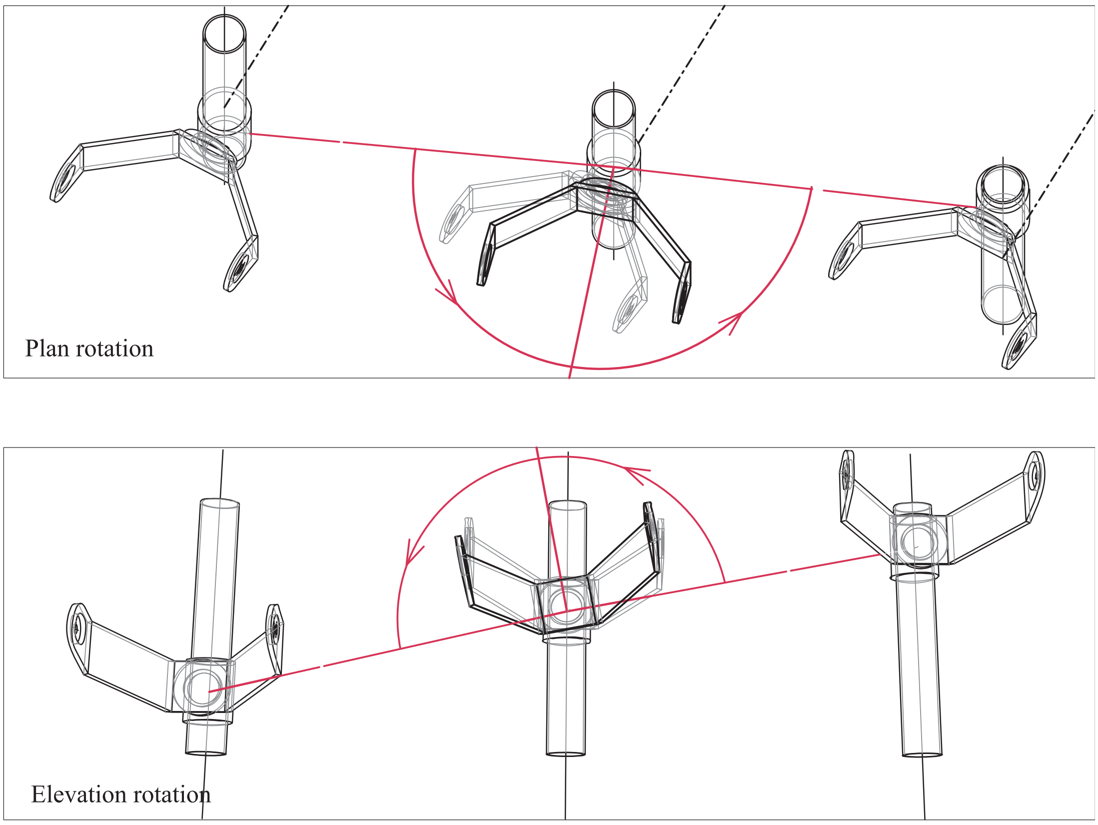


Figure 5.8: Bracket rotation principle.

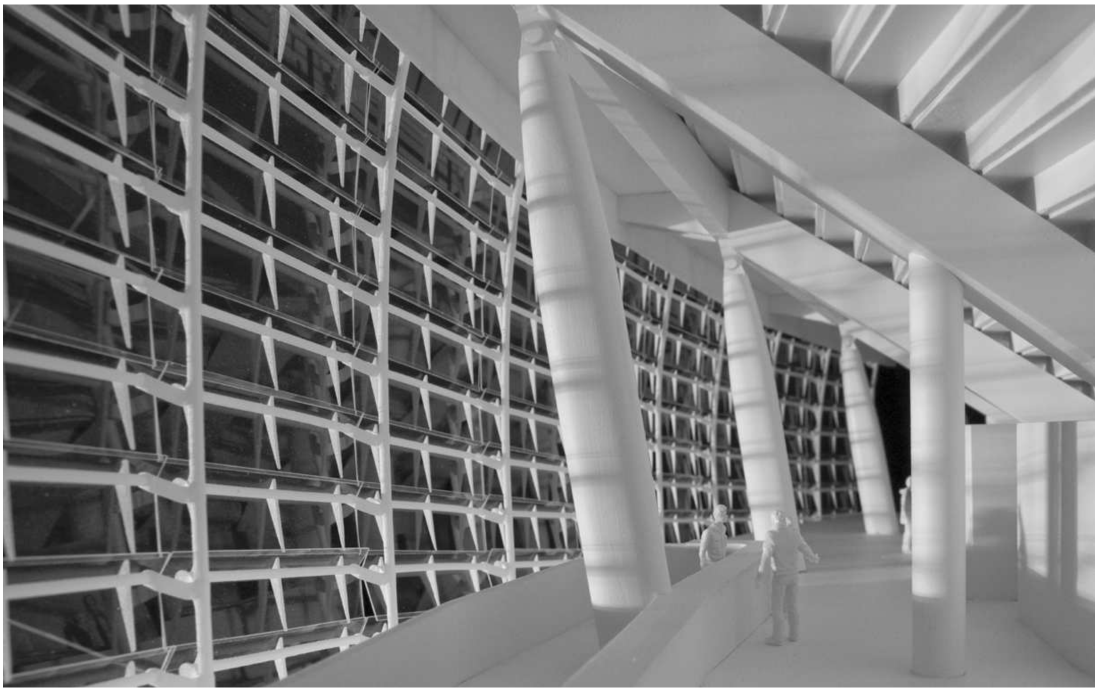
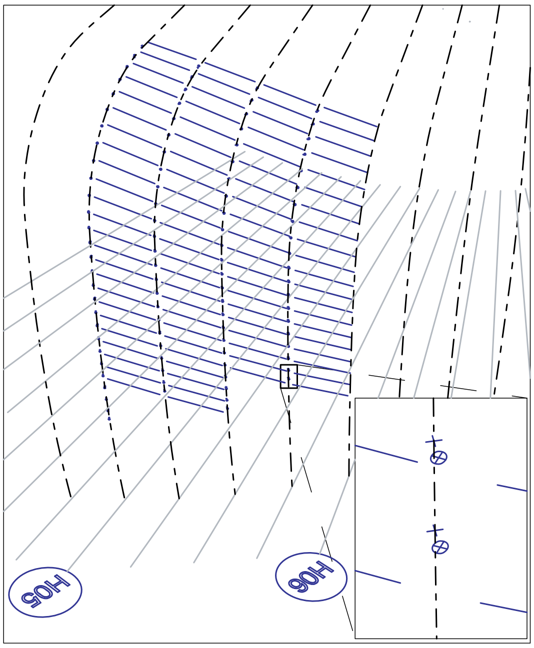


Figure 5.9: Physical model.

5.2.4 Construction documentation

The parametric modelling of the facade cladding system required all the parameters for configuring rotation angles of panels and brackets and spacings along mullions to be calculated. Initially this information was not represented in any way other than in the model geometry. In order to document the facade, this numeric information was extracted from the model and recorded in spreadsheets. Together with geometric models, this information was required as part of the construction documentation package (figure 5.10). This was issued in a form that allowed a sub-contractor to recreate the facade geometry. The data format was developed by closely collaborating with facade sub-contractors WC+CE.

The collaboration began with a three day workshop in WC+CE's offices in Basel. This involved the author and the lead facade designer from HOK and WC+CE's own design team. The geometric principles of the facade system were discussed and content and format of issued information agreed. Based on this, the architectural parametric model was extended to incorporate these requirements. In addition to the numeric information calculated to construct the parametric model, WC+CE required all panel lengths and two further angles for checking construction tolerances. The facade was broken into sections which were determined by the construction sequence and the radial grid. The contractual purpose of issuing construction documentation was to express the architectural design intent and provide enough information to completely reconstruct the system. WC+CE would then take full responsibility for the detail design of the facade with the knowledge that they had modelled it completely independently. However, WC+CE chose to use the architectural geometry issued by HOK as the basis for their detailed model of the facade system.



Inter-bracket distance

2937	3146	3401	3682
2990	3222	3491	3764
3063	3296	3574	3842
3125	3378	3648	3918
3188	3456	3720	3992
3253	3524	3798	4057
3311	3587	3871	4119
3375	3653	3930	4170
3435	3712	3997	4217
3484	3766	4041	4259
3526	3815	4087	4281
3561	3857	4105	4288
3596	3863	4110	4296
3601	3869	4119	4301
3608	3875	4123	4309
3613	3880	4129	4315
3615	3885	4137	4317
3621	3881	4144	4349
3626	3888	4147	4354
3629	3895	4035	4342
3626	3916		
3627	3926		
3630	3885		
3531	3881		

bracket angle 01

-18	-23	-28	-33
-21	-25	-30	-35
-23	-28	-32	-37
-25	-29	-34	-38
-26	-30	-35	-38
-27	-31	-35	-38
-28	-31	-34	-37
-28	-31	-34	-36
-27	-30	-32	-34
-27	-29	-30	-31
-26	-27	-28	-29
-25	-25	-27	-29
-23	-25	-27	-29
-23	-25	-27	-29
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-23	-25	-27	-29
-23	-25	-27	-29
-23	-25	-26	-28
-23	-25	-26	-28
-23	-25	-27	-29
-23	-24	-28	
-23	-24	-29	
-23	-24	-28	
-23	-25	-27	
-24			
-24			
-23			
-22			

bracket angle 02

11	11	13	17
8	8	9	9
7	6	4	4
4	1	0	0
0	-2	-4	-4
-3	-5	-8	-9
-6	-9	-12	-13
-9	-13	-15	-16
-12	-16	-19	-22
-15	-20	-24	-25
-20	-24	-26	-26
-23	-25	-26	-27
-23	-25	-27	-27
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-24	-27	-28	-29
-24	-27	-29	-29
-24	-27	-27	-28
-24	-27	-28	
-25	-27	-28	
-25	-27	-29	
-23	-26	-29	
-23			
-24			
-24			
-24			

checking angle01

92	92	92	92
92	92	92	92
92	93	93	92
93	93	93	93
93	93	93	93
93	93	93	93
93	93	93	93
93	93	93	93
93	93	93	93
93	93	93	93
93	92	92	92
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92	92	92	92
92	92	92	92
92	92	94	
92	92	94	
92	92	94	
92	91	93	
93			
93			
92			
92			

checking angle 02

90	88	88	86
89	88	88	87
89	88	88	87
89	89	88	87
89	89	89	88
90	89	89	88
90	89	89	88
90	90	89	88
90	90	89	89
90	90	90	89
91	91	90	89
91	90	90	90
90	91	90	90
91	91	90	90
91	91	91	90
91	91	91	90
91	91	91	90
91	91	91	90
91	91	91	90
91	91	89	91
91	91	83	
91	91	90	
92	91	90	
90	93	90	
83			
90			
90			
90			

Figure 5.10: Information issued for one facade bay.

5.2.5 Detail design

The detail design phase was driven by WC+CE's work and progress was monitored at a series of design meetings held at HOK's London office. These were attended by the main contractor (SISK), project manager, BH, HOK and when necessary other sub-contractors whose work interfaced with WC+CEs. At these meetings, WC+CE would report on the progress of the detail design, all involved would be able to comment. WC+CE's response to the undulating geometry of the stadium was a series of generic details that could accommodate a range of geometrically different fixing points.

In order to support the detail cladding design phase, the author, following a request by SISK, produced several, quickly constructed parametric models. These were used to determine ranges of angular and dimensional differences that the generic connections needed to accommodate (figure 5.11). Other models were developed to check for clashes between the facade panel brackets and the connection between mullion and floor slab (figure 5.12). Parametric modelling by the author was also used in the development process for a series of other detail design elements. These included a rationalised acoustic panelling system (figure 5.13), a strip of gutter panels at the base of the facade (figure 5.14) and checking for clashes between all neighbouring panels (figure 5.14).

In addition to the design work undertaken for the main contractor, the author also undertook a series of checking procedures for HOK to ensure coordination across all packages. This involved developing existing models to incorporate details proposed by more than one contractor such as between steel design and the facade system. These checks enabled HOK to avoid extensive manual work and approve the detail design proposals for construction.

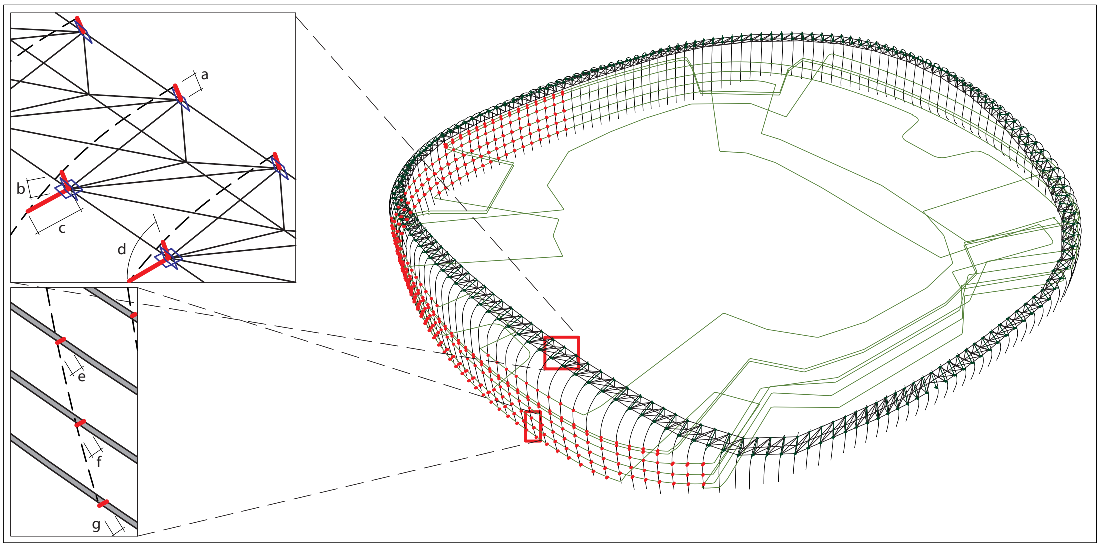


Figure 5.11: Measuring tolerances.

5.3 Analysis

The LRS case study provides an opportunity to examine several of the key areas identified in the literature review. These are discussed in this section. Crucially the project takes advantage of possibilities described in theory but unfulfilled in the practical literature. The cladding design task demonstrates how parametric models assist in the development of problem descriptions through knowledge acquisition. Use of parametric design at the conceptual stages in the cladding design provides evidence to support the view that

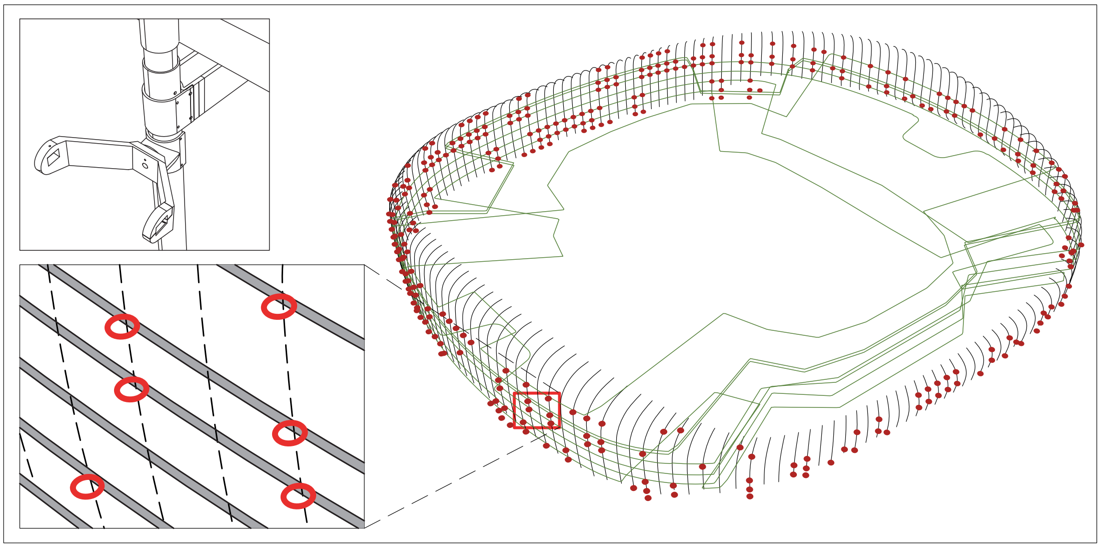


Figure 5.12: Clash locations. Potential clashing elements (top left). Clashes flagged with circles (bottom left).

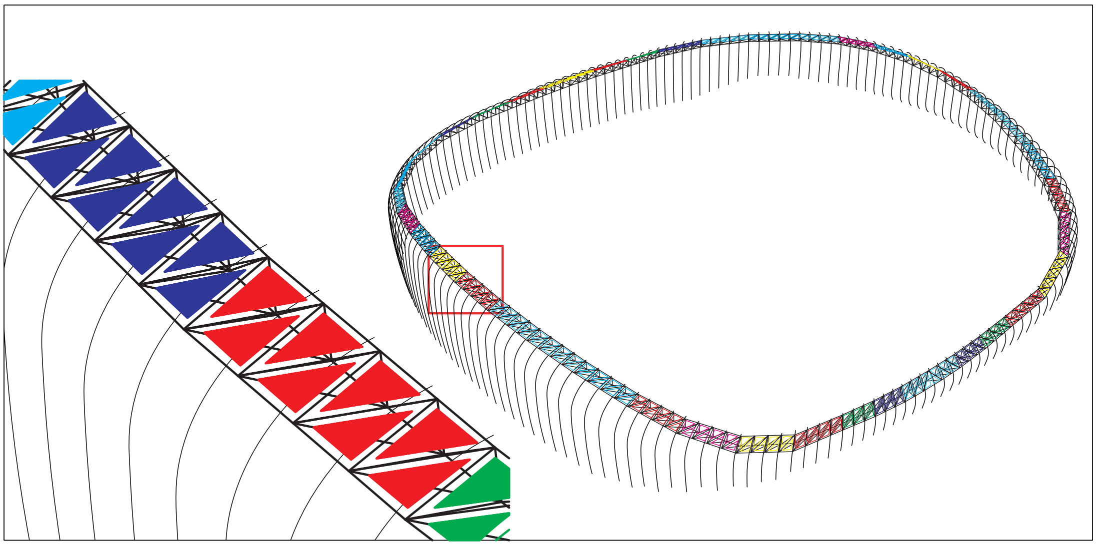


Figure 5.13: Acoustic panels rationalised and grouped by colour.

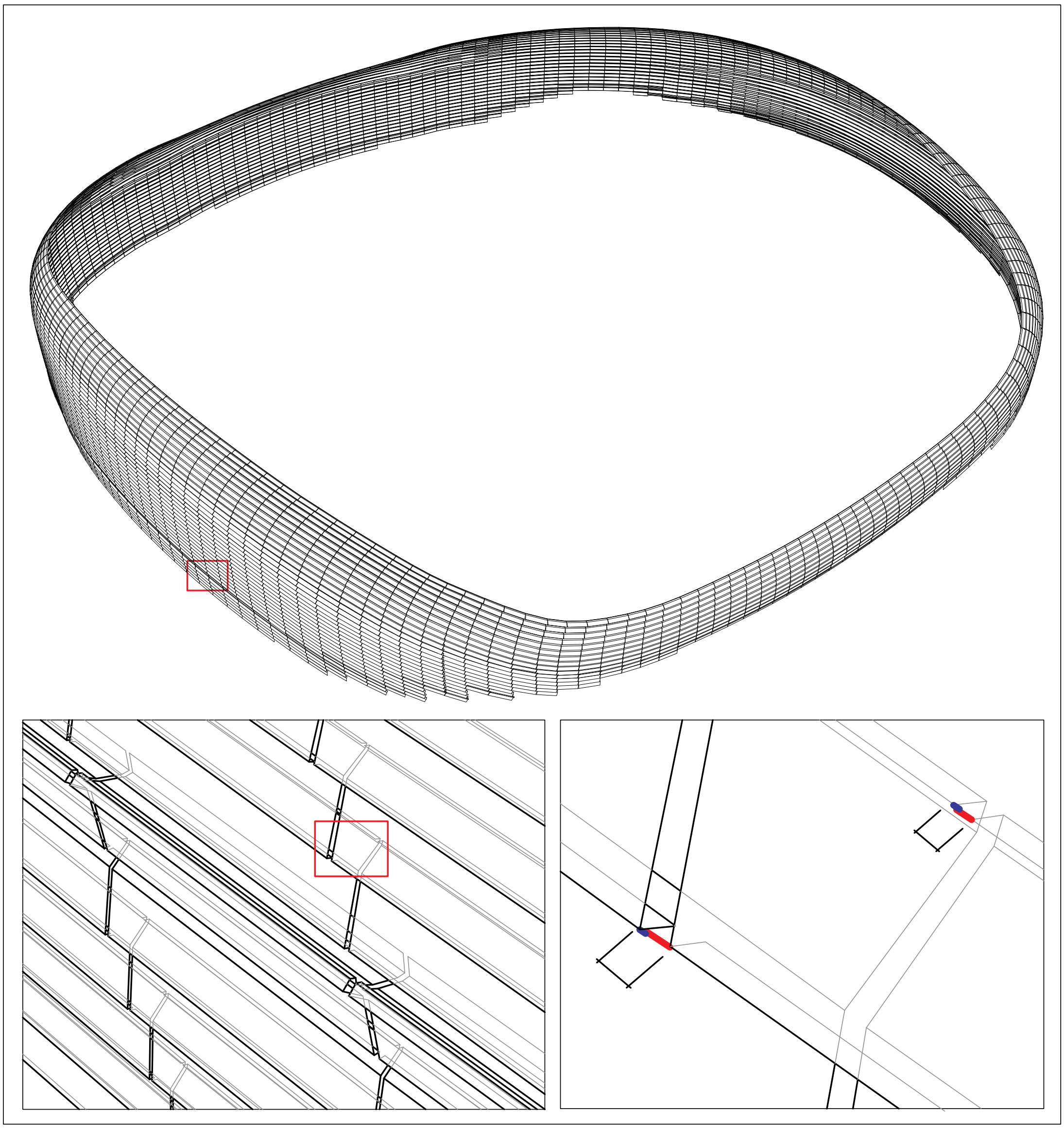


Figure 5.14: Generation of facade. Gutter panels (bottom left). Checking gaps between panels (bottom right).

parametric modelling can be beneficial at early stages of design. Part of this process illustrates, in detail a ”propose, critique and modify” design model that was described as a method for assessing alternative designs. Theoretical literature also suggested possibilities for sharing parametric definitions, LRS demonstrates this. The architect’s parametric model was shared with structural engineers illustrating the use of a shared parametic definition.

Developing the envelope geometry contributes detailed descriptions and further examples of a series of parametric tasks; translation, fragmentation of control system, fragmentation of problem, use of multiple representations and defining initial parameters.

The detail design phase of the case study introduces a new parametric design task, cross-contractual skill sharing. This involved assisting sub-contractors in the detail design development with parametric design skills that were enhanced by knowledge of the design intent and involvement in earlier design stages. Contractually the position of this task was unclear, but there were benefits to all involved; architects, engineers, contractors and sub-contractors. The problems resolved were at the interface of different specialities where collaboration is essential.

5.3.1 Development of problem description and knowledge acquisition

When considered as a design task in its own right the cladding design process demonstrates how parametric modelling can help develop a description of the problem. The extent of the description at any point in time is dependant on what is known about the problem. Therefore the process of problem description development can be considered as a series of knowledge acquisition steps. ”Design prototypes” described by Gero (1990) propose that design problems can be represented by three distinct knowledge types; function, behaviour and structure (see chapter 3). At each step of the design process new knowledge is acquired in one of these areas and the description of the problem becomes clearer. The LRS cladding design task demonstrates how a ”design prototype” can be applied to a practical architectural problem. This suggests that parametric modelling can be seen as a system of knowledge acquisition. The way in which the cladding design task demonstrates the development of a problem description and how this relates to ”design prototypes” is dealt with in detail in Hudson (2008c). This section summarises the key points in that paper.

The cladding design task proceeded as a series of iterations, which started with an incomplete description of the problem. At each stage parametric models were produced that represented the current level of knowledge of the problem. These quickly produced models which formed a basis for decision making. Decisions made introduced new knowledge and the problem description became more clear. This knowledge was then used or captured as part of the model in the following iteration.

The initial stage used parametric modelling to define a cladding system consisting of panels following the underlying geometry and simply represented them as a series of four sided polygons. Several different versions of setting out methods were investigated. These included various patterns, investigations into rain runoff direction and flat and twisted panels (figures 5.15, 5.16 and 5.17). Several quickly produced parametric models provided the design team with grounds to make decisions regarding the function and appearance of the system. The knowledge gained improved the description of the problem and informed the next iteration.

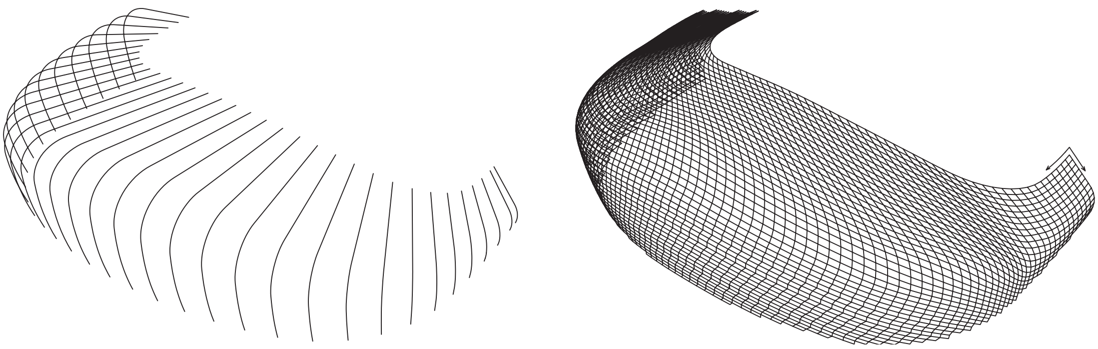


Figure 5.15: Left: Underlying geometry. Right: Rectangular array of panels over surface.

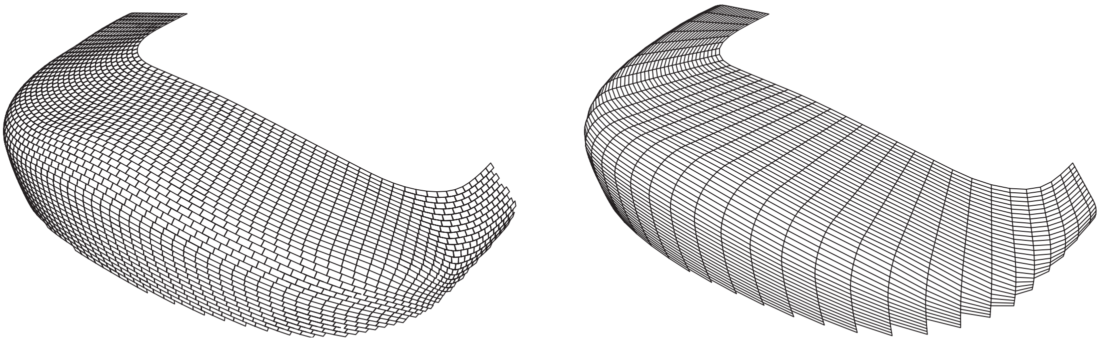


Figure 5.16: Left: Brick bond setting out. Right: Array of panels with varied numbers in each bay.

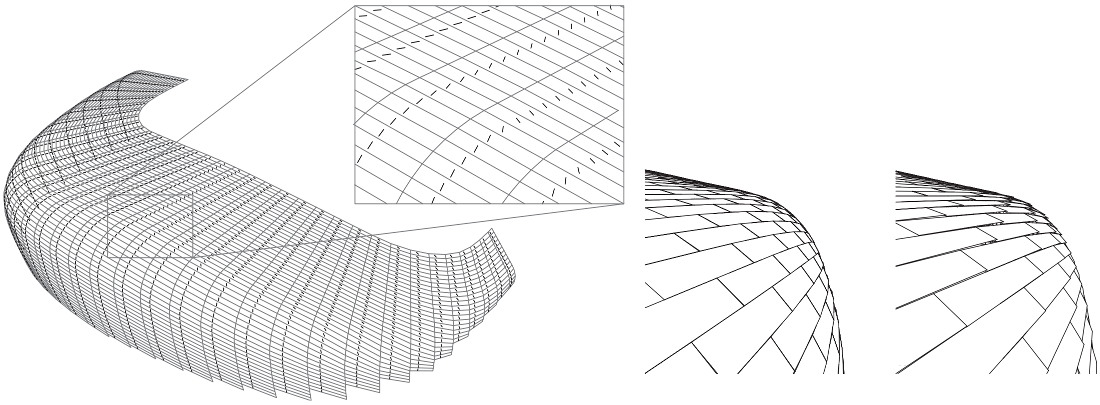


Figure 5.17: Left: Water run-off directions. Right: Visual comparison of warped and planar panels.

The next step involved investigating two options for panel assembly systems which were driven by the involvement of expert manufacturing knowledge (figure 5.18). Using the geometry of these, parametric models were constructed to produce three-dimensional models for aesthetic evaluation and quantitative information to evaluate for cost, both to deliver and maintain each system. Based on this evaluation an assembly was selected. This decision imposed geometric constraints on the model, panels needed to be planar, use a standard profile and bracket to fix back to facade structure. These constraints reduced the range of possibilities and in doing so further improved the problem description.

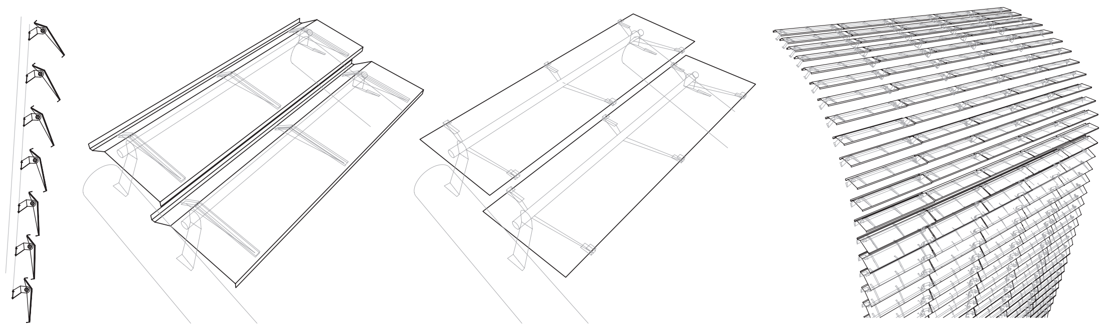


Figure 5.18: Left to right: Facade section. Polycarbonate panel assembly. Glass panel assembly panels. Panels on facade

The next phase was focused on developing these requirements. The result of this was the development of standardised brackets for supporting panel assemblies and the algorithmic knowledge for automating the positioning of these across the entire facade. The proposed brackets had two axes of freedom and an algorithm was required to calculate these angles based on the position of surrounding panels (figures 5.7 and 5.8). Using this algorithm it was possible to produce three-dimensional models to test that the proposed system worked over the whole stadium. Based on this, the dimensions of the brackets were refined. Models generated three-dimensional geometry which was used to produce rendered images for aesthetic evaluation in client presentations and at planning approval meetings.

At this stage the problem description was quite well defined. The penultimate iteration of the design process involved developing the parametric facade model to provide a way to balance three conflicting criteria; facade ventilation, ingress of wind blown rain and an aesthetic concept. This iteration demonstrates the way a ”propose, critique and modify” design sequence plays a part in practical parametric design. This is discussed in detail in the next section and figure 5.19 illustrates the iterative process that was captured in this stage.

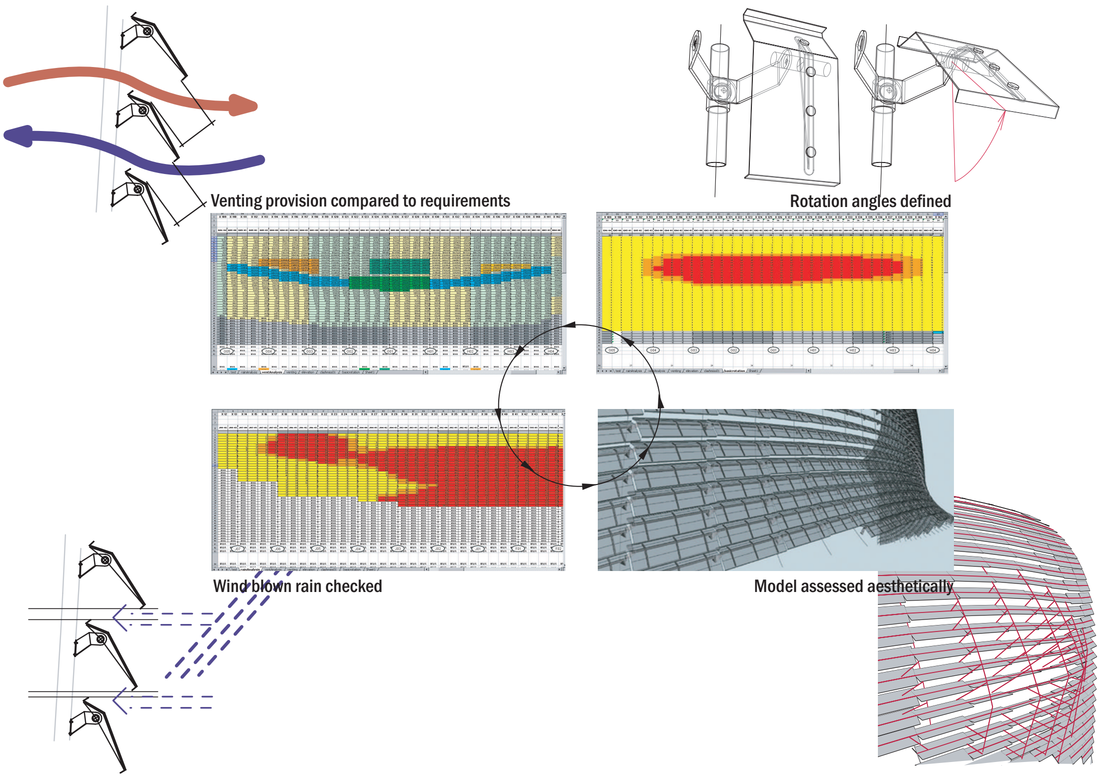


Figure 5.19: Model for panel system development.

The final iteration of the cladding design process involved developing the method for construction documentation. Through close collaboration with the facade sub-contractors a data format for the issuing of information was developed. In this way the specialist knowledge of the facade sub-contractors became captured in the model. The facade was broken into seven sections defined by the proposed construction sequence. Each section was sub-divided into structural bays. For each bay two geometric models were produced and for each panel five numerical parameters written to cells in a spreadsheet. The process was tested with a full scale mock up (figure 5.20).

Figure 5.20: Cladding mock up.

The project demonstrates that it is possible to use parametric modelling to develop problem descriptions. It is important to start working in a way where models are initially treated as disposable and they are discarded when they do not yield useful results. In this way the rigid structure of the parametric model will not restrict design direction. Later, as the problem becomes clearer, it may be possible to develop more refined and stable model foundations onto which more disposable modules can be plugged in and tested. Use of placeholders which define simplified versions or approximate guesses like the initial panel models will allow modelling to progress with incomplete knowledge. Based on these, design decisions can be made, as knowledge becomes available placeholders can be substituted for more precise descriptions.

5.3.2 Propose, critique and modify

Propose-Critique-Modify (PCM) was described in the theoretical literature as a means of assessing alternative designs. One iteration of the cladding design process demonstrates how PCM can be applied in a practical context. The proposed cladding panels had a lateral axis of rotation and this allowed the system to operate like a shingle roof. The axis also meant

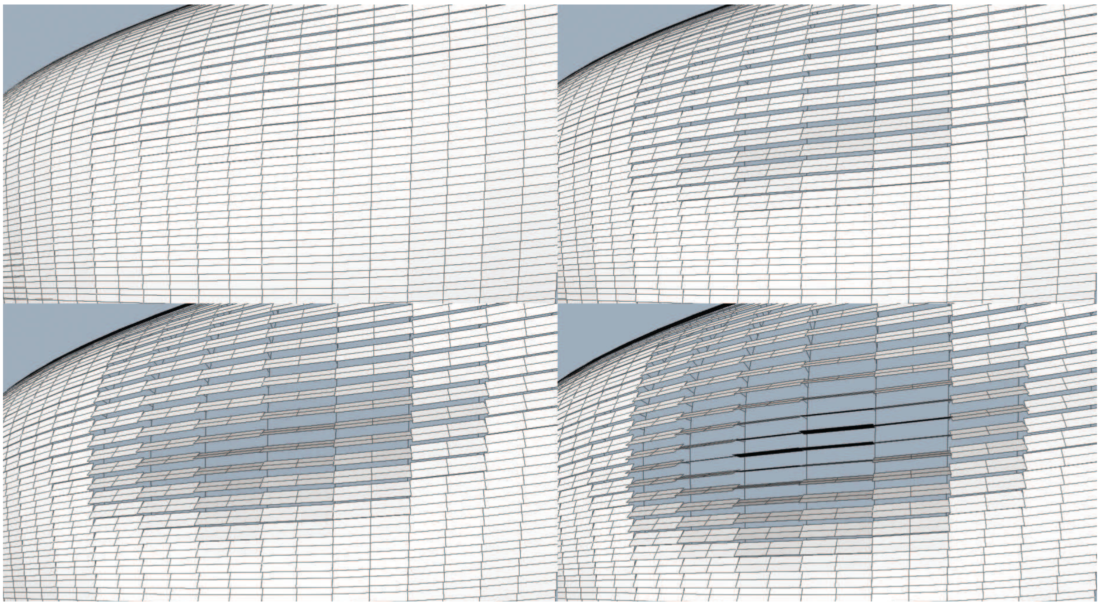


Figure 5.21: Cladding concept.

some panels could be fixed in an open position to provide air intake and exhaust for air handling units located behind the facade (figure 5.6). The aesthetic concept was defined using a series of quickly produced simple models that demonstrated how areas of open panels could be ”blended” into the surrounding facade by smoothly reducing the open angle in panels around the open area (figure 5.21). These simple models captured a description of the design intent over a small area but a system to control the whole the facade was required.

This was implemented by mapping individual panel rotation angles contained in cells within a spreadsheet, representing the facade, to the parametric model (figure 5.22). Within the spreadsheet the location and extent of open areas was specified and fall off in angle was defined by functions.

The design task for this iteration was to specify rotation values to meet the demands of the aesthetic concept while providing requirements for intake and exhaust areas supplied by mechanical engineers (figure 5.23). In addition it was necessary to limit the chances of wind blown rain through vertical gaps between panels where blended areas extended beyond the air handling units (figure 5.24). A design loop was implemented in the parametric model whereby rotation values were proposed, ventilation areas and wind blown gap dimensions written to a spreadsheet and a three-dimensional model produced (figure 5.25). Using these numeric and geometric representations a configuration could be proposed and then critiqued.

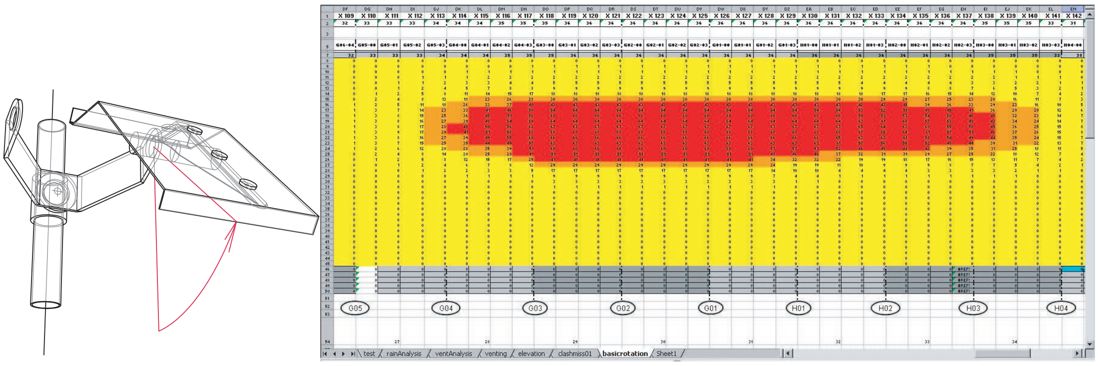


Figure 5.22: Panel rotation values.

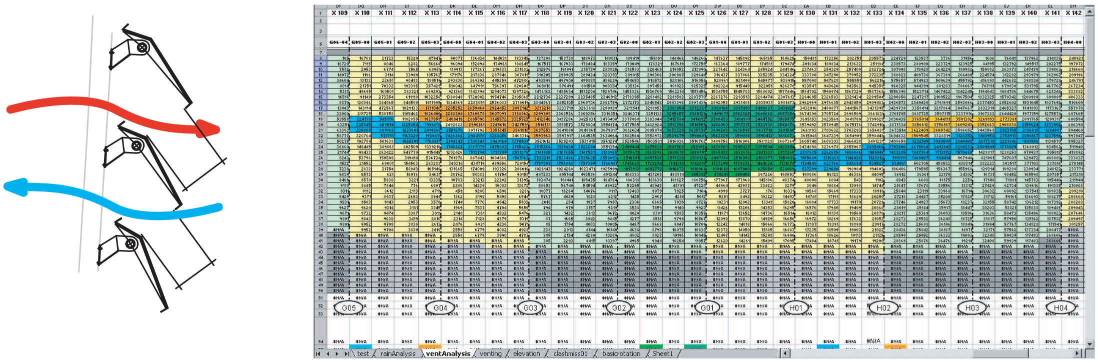


Figure 5.23: Panel ventilation areas.

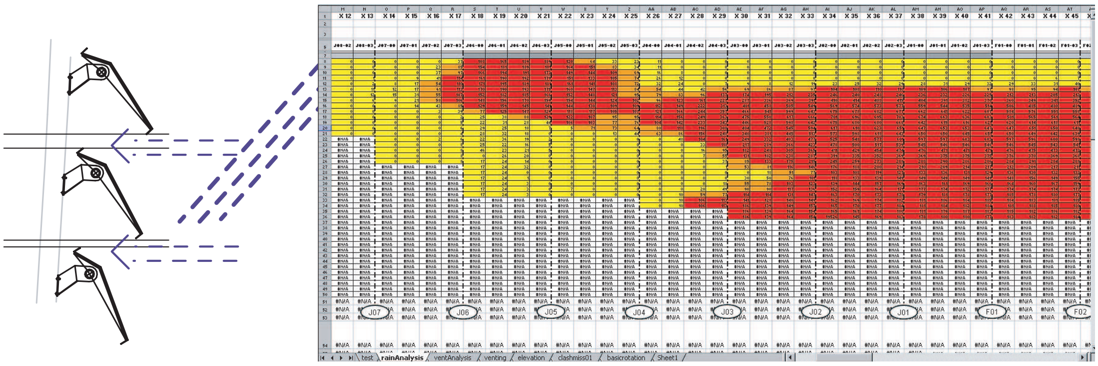


Figure 5.24: Panel wind blown dimensions.

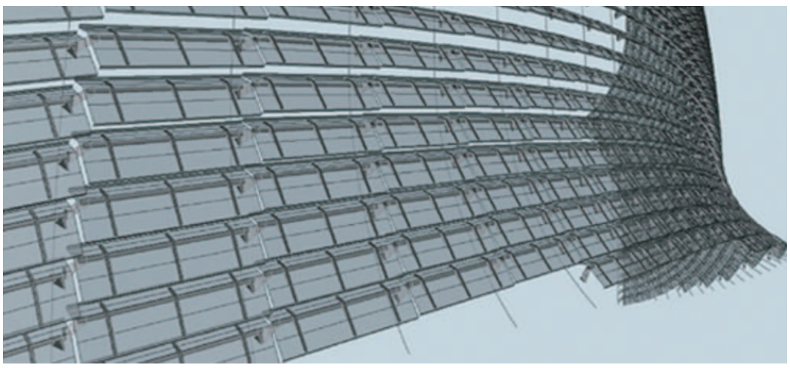


Figure 5.25: Model for aesthetic check of panels.

The theoretical description of PCM suggests that knowledge of model structure and ability to select a design focus are important considerations. The critique part of the process is regarded as diagnostic and indicates how to change the model. Therefore, in order to diagnose and implement the suggested change, knowing how the model works is crucial. The theory also suggests that the assessment process is easier in a multi-criteria situation once a particular design focus is chosen, which involves prioritising one criteria over others. With the cladding design task this was found to be the case. The focus was the provision of ventilation to air handling units. The ventilation area provide by each panel was mapped to the spreadsheet-elevation. Examining this showed areas provided by each panel and the total for an entire set of panels. Similarly the effect of wind-blown rain could be seen panel by panel. Because these spreadsheet-elevations were representations of the facade it was possible to deduce the corresponding rotation values to modify to improve the ventilation values while minimising the effect of wind-blown rain. Figure 5.26 illustrates the final result of this process showing a detail of a completed portion of the facade.

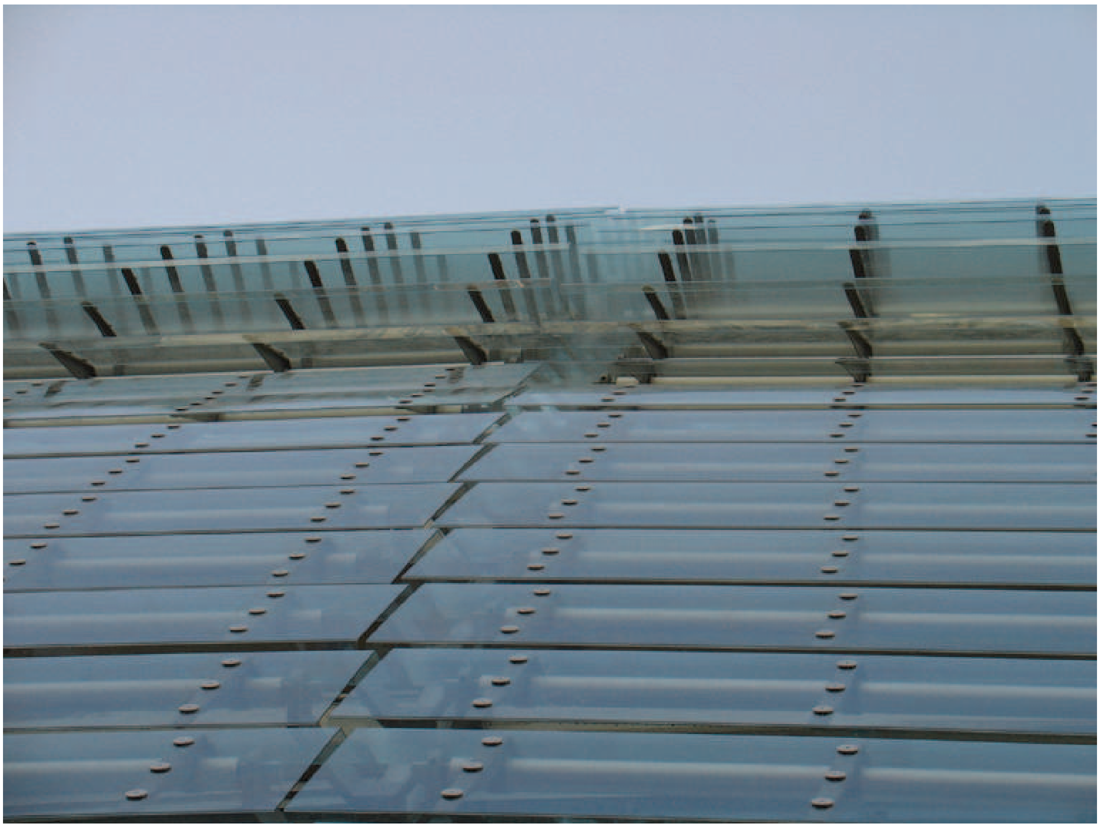


Figure 5.26: Detail of built facade.

5.3.3 Sharing information

Theoretical literature described the possibility of sharing parametric models, which was unfulfilled in the practical literature. Parametric modelling of LRS demonstrates how a model definition was shared between HOK and BH. BH were issued a parametric definition of the envelope geometry as a script file along with a set of corresponding numeric input parameters stored in a spreadsheet. The structural definition was undertaken with the same software (GC) and used the envelope definition as its basis. Changes to the geometry by HOK were recorded in a spreadsheet which could be reissued, the structural model would upload these new parameters and an updated model defined.

Implementing this process on LRS indicated several considerations required when implementing a shared parametric definition in practice. The first is the importance of making early agreements in terms of naming conventions of geometry within the model and agreeing procedural orders for generating the geometry. Early meetings were held between BH and HOK to agree naming conventions and parametrisation methods for the envelope model. Careless changes to naming of geometry and order of construction to HOK's parametric model during the design process illustrated the problems caused by straying from agreed conventions.

The speed at which these problems could be resolved was limited because the author was employed as HOK's only parametric modeller and was operating as an independent consultant. Detailed knowledge of the model was not shared, so fixing problems could only be undertaken by the author. BH also had a single person responsible for managing the structural modelling. A pair of parametric modellers, each working for HOK and BH, and familiar with the models, would have avoided this. These single conduits, were a weakness as model fixes and structural geometry updates could only be processed when that person was available.

It was important to clearly identify the ultimate responsibility for defining parameters in this process of sharing a parametric definition. The shared system used for LRS restricted all changes to the envelope geometry to HOK. However, if these could have been relaxed, BH would have been able to make adjustments to the geometry of the envelope, and they may have been able to improve the efficiency of the structure, demonstrate savings and make recommendations for geometric improvement. HOK could have acted on this and implemented changes to parameters within their responsibility. Allowing others the opportunity to make adjustments to geometry could enhance the design process by establishing a more collaborative environment.

5.3.4 Translation

Translation was identified as a parametric task in the practical literature. It is concerned with taking a design that has been instigated without the benefit of parametric tools and producing a parametric model that captures the design intent. The LRS case study reveals the process of translation in a situation where the practice had no previous experience of using parametic models and the author had limited experience working with the parametric software GC. This situation is likely to be typical of practices making their first experiments with parametric design.

Translating the existing design into a parametric model was the first task for the case study. This task lasted a few weeks and was also treated as a test phase which allowed the team to be certain they wanted to commit to a parametric approach, provided an opportunity to prove to senior architects it would be beneficial, and to check that the team were happy to work with the author.

The translation for LRS was undertaken using the CAD geometry of the stadium that had been produced before parametric design involvement. Conversations with members of the design team responsible for producing the initial geometry also contributed to the process. Translation and capturing design intent required gaining an understanding of what HOK wanted to do with the parametrised geometry, how they thought it should behave and how they wanted to control it.

Conversations with the design team indicated their intentions for the parametric model. It had to allow accurate manipulation of the envelope geometry to provide aesthetic control. The model needed to include automated extraction of sections and plans, to be cut from a surface representing the envelope, as these would form the basis for two-dimensional drawings. The parametric model was also required to provide a starting point for the development of the cladding system, and as a means to communicate the geometry to the structural engineers.

Developing an understanding of the desired geometric behaviour was a more extensive task. The first step involved gaining an understanding of the reasons and methods used to generate the geometry used for the planning submission. The planning model had been created intuitively using Rhinoceros (McNeel, 2007) by various members of the design team. Descriptions of the methods used varied between members of the design team. They were recorded informally as sketches or presented verbally. Inspection of the model indicated an original construction method consisting of varying radial sections.

To develop a parametric version, the sections were examined and discussed with the original modellers in order to establish the rules. This led to an understanding of the required geometric behaviour and allowed a more formal methodology to develop. The goal was to establish a single geometrical rule set for defining a section that could be used throughout the stadium, easily controlled and manipulated.

As rules and relationships were extracted from descriptions provided by the members of the concept design team, small models could be constructed to test the proposed geometric principles. Ranges of possible variation could be checked by manipulating models on screen in the presence of the design team. Geometric behaviour could be demonstrated and output could be compared to sections from the CAD model. Models that gave unsatisfactory results were abandoned and new ones quickly developed. Where models were found satisfactory these formed the basis of the next iteration. In this way the parametric definition of the sections gradually emerged. This illustrates the use of "propose-critique-modify" as an integral part of the translation process. The theoretical literature identified this as a method of design, and in this case it is used for the design of the parametric model.

In a similar fashion, quick models were developed to examine how these sections could be controlled. Each proposed method was evaluated by the design team to check it met their expectations and the anticipated range of variation could be achieved. Each section took input from a range of sources and the resulting control system reflected this.

In a way similar to the process of developing problem descriptions, the translation task benefited from quickly produced models treated in a disposable way. Design intent was rapidly translated from CAD models and verbal descriptions to a parametric form by treating the models as disposable.

5.3.5 Fragmentation of control system

Fragmented and hierarchical control mechanisms were recognised in the practical literature and the use of fragmentation as means of simplifying complex tasks was described in the theoretical literature. LRS provides an opportunity to examine this fragmentation of control system in more detail. The control system for LRS was fragmented and consisted of values in a spreadsheet, static geometry and graphical control devices called law-curves.

The envelope geometry can be regarded as equivalent to the ”design surface” described in the practical literature. In this project the surface was only used for extracting two-dimensional drawings. The surface was defined with structural centre lines. These centre lines controlled the structural geometry and the cladding system.

The structural centre-lines were controlled on-plan by two planar curves and vertically by a set of planar law-curves. The planar curves described the building footprint and inner roof-edge. The law-curves described the vertical variation of key sectional points around the stadium. The law-curves were defined with sets of coordinates stored in a spreadsheet and were controlled by editing these values. The spreadsheet also contained the parameters for the footprint and inner roof-edge of the building. Positions of the structural centre lines were defined by a radial structural grid that was a referenced static geometry file.

Storing all numeric parameters in a spreadsheet format made it easy to record the entire set of parameters. Law-curves provided a visual two-dimensional control mechanism for a three-dimensional form. Provided the law-curves were smooth, the stadium geometry would be smooth. Using CAD geometry to define the structural grid meant it could be controlled by anyone with basic CAD skills.

The simplicity of the system meant that potentially any design team member could open the model and have a high level of control by editing values, observing the law-curves or by changing the grid. In reality, model controllers found the concept of the fragmented control system too complex. Users were familiar with architectural computer models where model files can be simply opened and viewed. The parametric model required execution to see the geometry. Changes to values in the spreadsheet had to be incorporated by pressing an “update” button.

All changes and manipulations of the model were undertaken by the author. This single conduit had similar consequences to those found in sharing the parametric definition. When model changes or updates were required the rest of the design team had to wait for the parametric modeller to implement those changes. Sometimes these delays had implications on the speed at which information was passed onto external specialists. The result of this was occasional moments of high stress and rushed work causing delays in progress and increasing chances of error.

5.3.6 Fragmentation of problem

Fragmenting problems to make them more manageable formed part of the underlying design theory. This process can be observed in the LRS project both in the control hierarchy described above and in the general organisation of the parametric system. Figure 5.2 shows the top level fragmentation of the parametric process. Fragmentation of the cladding design process is illustrated in subsections 5.3.1 and 5.3.2. The structural component was also broken into smaller chunks consisting of primary, secondary and tertiary structure, details of which are beyond the scope of this thesis. The envelope geometry was fragmented into a set of sub-problems. These were tackled in the translation stage and included developing the sectional geometry, developing the definition of the tangential plan curves and defining the law-curves based on numeric information from a spreadsheet. Each of these could be broken down into further sub-tasks relating directly to implementation with the specific software. Given clear interfaces between sub-problems a team of parametric designers could have tackled these simultaneously and then combined them into a single model.

5.3.7 Multiple representations

Designing with multiple representations was described as beneficial for design problems in the theoretical literature. This could be observed in the practical literature but it was not explicitly described as such. The parametric process for LRS demonstrates how several representations were used and how the project benefited primarily through the communication opportunities they provided.

The three most extensively used representations of the model were the script file, the spreadsheet and CAD geometry. The script file described a sequence of geometric rules, relationships and instructions to read parameters from the spreadsheet. As these were executed, three-dimensional geometry was produced. This was then rendered to provide a visual representation of the stadium. The law-curves can be regarded as another representation of the model as they describe variation of form around the stadium. The cladding design, construction documentation and detail design phases extensively used spreadsheets as a representation of the elevation. Numeric data was stored in cells that were associated with particular panels or brackets. These spreadsheet-elevations also used conditional colouring of cells to give a visual interpretation of the areas of open facade or areas susceptible to wind driven rain (figure 5.24). CAD geometry was imported and defined the radial structural grid. This could be edited and updated by any one with basic CAD skills. Physical representations created from parametrically generated information also played a part in the design process. Two full-scale mocks were constructed along with scaled models and a wind tunnel model.

Alternative modes of representation used on LRS provided different ways to communicate model configuration, visualise the control system, assess the geometry in terms of aesthetics and performance and to share information. Multiple representations were considered a necessity as they ensured implications of the design could be communicated in a variety of ways to various people helping move towards a completed project.

5.3.8 Defining initial parameters

Theoretical literature suggested that parametric processes are instigated by assigning an initial set of parameters. For LRS, initial parameter values for the form were extracted from a static model produced prior to the development of a parametric model. These values provided the initial values for parameters used to construct the law-curves. This defined a starting geometry and the first task was to refine the parameters so that the rationalised parametric geometry matched previous models as closely as possible. This process involved generating plans, sections and elevations from the parametric model, which were overlaid onto the originals, and required changes noted (figure 5.27). Iteratively, the geometry moved towards a close match of the original, at each stage a new set of adjusted parameters was proposed, the geometric implications assessed against the originals and then modifications made to parameters.

In some cases arbitrary parameters had to be defined in order to configure the model. An example of this was the use of the back of seating-bowl to arbitrarily define the level of a tangent between two sectional arcs. Working with this as a placeholder parameter, it later became apparent that the sectional geometry was not aesthetically satisfactory for HOK. A further parameter was added controlling the level of the tangent relative to the back of seating-bowl and it was then possible to define a satisfactory form (figure 5.28).

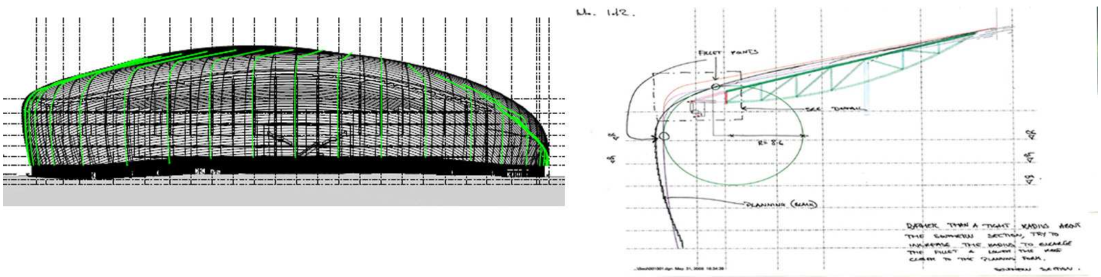


Figure 5.27: Matching form.

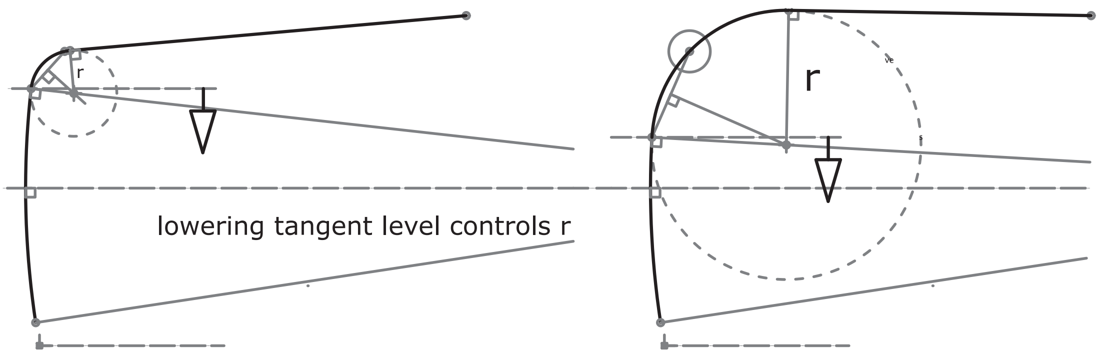


Figure 5.28: Adding aesthetic control.

Assigning a complete set of initial parameters enables the design process to begin. Where a parameter is unknown a best guess is better than a null value. The arbitrary parameter used for the LRS section demonstrates how the use of a placeholder allows the design process to progress. This relates to the way that parametric tools can be used to develop design descriptions which was demonstrated in detail in subsection 5.3.1. In this example progress is not prevented by a lack of description, instead a temporary substitute is used and then later in the process this is adjusted to reflect the design intent when it becomes apparent.

5.3.9 Operating across contract boundaries

It is proposed that the detail design stage for LRS demonstrates a further parametric task which is concerned with reaching across contractual boundaries in order to assist the progress of the project. LRS demonstrates how, during the detail design stage of the project, the skills of the parametric designer responsible for the architectural model, could be applied to tasks being undertaken by facade sub-contractors. This involved assisting in developing detail design by taking rules and dimensions of proposed connection details and setting up algorithms to repeat these right around the stadium. Other repetitive tasks were captured as parametric algorithms which sped up the rate of work. This provided the architects a way of checking details but also informed facade sub-contractors of problem areas and checked that the proposed generic detail satisfied their criteria.

It should be noted that the parametric skill transfers occurred only between HOK and WC+CE and not between HOK and BH. BH had in-house parametric capacity whereas WC+CE did not. BH's parametric skills facilitated the innovative sharing of parametric definitions. This was not possible with WC+CE, so rather than share the model, the author's skills were shared or transferred across the contract boundary.

This task challenged traditional contractual arrangements, but was found to be extremely beneficial for the project to have a single parametric modeller operating on behalf of both the architect and the facade sub-contractors. The workflow suggested by this observation is one where the skill set of the architectural parametric modeller can be shared amongst the wider design team outside of the architects office. This differs from other workflows observed in practice (chapter 4). This firmly links parametric responsibilities with the architect but allows for much more direct working relationships with contractors. Other workflows that included direct working relationships with contractors were dependant on parametric modelling that was undertaken outside of the architectural practice. Where parametric modelling was undertaken within the practice, the modeller was prevented from directly working with contractors by an indirect flow of information. The geometry method statements used by Foster and Partner's and the shared BIM models used by Frank O Gehry and Partners prevent direct working relationships between contractors and parametric modellers. Not using a well constructed architectural parametric model is potentially a waste of effort. LRS demonstrates how architectural parametric models can be quickly and simply extended to deal with more detailed concerns normally beyond the remit of architectural work.

5.3.10 Checking detail design

The detail design phase for LRS demonstrates that checking design details developed by sub-contractors can be undertaken parametrically. This had not been identified as a parametric task by either the theoretical or practical literature. The detail checking on LRS required existing parametric models to be extended and new models to be constructed in response to the information returned to HOK by WC+CE. This was not in the original scope of parametric work but it became apparent later in the project that this was the most efficient means for checking proposed details.

5.4 Summary

Figure 5.29 is a graphical summary of the contribution that the LRS case study makes to the objectives of this thesis. The primary objective was to identify the tasks the parametic designer is engaged with. The figure is the task structure diagram introduced in the literature review to illustrate the role of the parametric designer. Text and boxes shown in bold illustrate the areas that the LRS either adds to this structure or where it provides practical examples of areas identified in the literature review.

The LRS case study contributes several examples of unfulfilled possibilities identified in the review of theoretical literature. The cladding design phase of the project demonstrates how parametric modelling can be used to *develop a problem description*. This was observed as an incremental process and proceeded in steps where knowledge was acquired and then captured in the models of next iteration. Early stages of this were dependant on an approach where models were treated as disposable, quickly constructed and quickly critiqued. Later

Task	Sub-task	Procedure	Practice example	Case study example
Create Model	Develop problem description	Assign function, structure, behaviour		LRS
		Identifiy parameters		LRS
		Fragment problem		LRS
		Propose-critique-modify		LRS
	Externalise ideas	Use library / memory		
		Case retrieval		
		Declare parameters rather than shape		
		Fragment model		LRS
		Multiple representations		LRS
		Propose-critique-modify		LRS
	Capture design intent	Translation	03 11 13 16 22	LRS
		Propose-critique-modify		LRS
	Rationalisation	Post-rational	06 09 11	
		Matching geometry	06 09 11 14	LRS
		Reduce geometry to simple elements	06 09 11 14	
		Flat panel	06 09 11 14 26	
		Pre-rational	05 07 08 21	
	Control	Design surface	02 12 13 15 21 22 28	LRS
		Fragmentation / hiearchy of control	21 12	LRS
Design investigation	Find appropriate parameters and generate alternatives	Assign initial values		LRS
		Reduce solution space using amplifiers		
	Assess alternatives	Propose - critique - modify		LRS
	Generate and Test	Multiple representations to assess:		
		environmental analysis	11	
		structural	26 27	
		construction logic	22	LRS
		aesthetics		LRS
Construction documentation	Share information	Geometry method statements	FP	
		BIM models and external manager	FG	
		Static model files	SOM	
		External parametric with direct links to sub-contractors	DTP	
		Share parametric defintion		LRS
		Cross contractural boundaries		LRS
		Check detail design		LRS
Split Opinions + critique	Point of parametric application			LRS
	Depth versus breadth			
	Use and development of libraries			

Figure 5.29: LRS summary.

stages involved more refined foundation models onto which disposable modules could be attached to continue to develop more detailed aspects of the problem description.

Sharing a parametric definition of the envelope geometry is a procedure not documented in practice. LRS demonstrates how this could be implemented provided early agreements in parameter responsibility and model logic were made and adhered to. The case study suggests the need to establish some form of redundancy in the parametric modelling skills of a practice to avoid impeded workflows. Relaxing parameter responsibilities may have been an opportunity for structural engineering to inform architectural geometry configuration. In scenarios where the proposed workflow involves a model developed and maintained by one person and used by others a period of familiarisation or training is suggested.

Iterative development of the configuration of facade panels illustrates a practical application of the *propose, critique and modify* design model. Important to this were knowledge of the model structure, ability to select a design focus and assess the design based on that. Assessment combined with model knowledge indicated how to improve the design.

The case study also provides further details and examples of tasks and considerations identified in the literature review but only partially observed in practice. These included *translation, fragmentation of control system, fragmentation of problem, use of multiple representations* and *defining initial parameters*.

The *translation* process highlighted the need for verbal communication and a disposable modelling approach, which allows the design intent to be identified rapidly. The project illustrated a *fragmented control* system and suggested the potential for this to involve multiple controllers with varied parametric skill levels. Similarly the observed *fragmentation of the problem* lends itself to an approach involving multiple parametric designers working with clearly defined interfaces. Use of *multiple representations* was primarily employed here as a means for communicating the design and visualising the control system. This helped the wider construction team and members of HOK.

The project contributes to the debate over the appropriate point of parametric involvement in a project. Use of parametric modelling from the outset of the cladding design process and the example of using partially complete sets of parameters are examples that counterpoint the existing arguments (Burry, 2006; Maher, 2006) for later application of parametric design.

Finally the case study results in the identification of two further sub-tasks for the parametric designer. *Cross contractual boundaries* is concerned with taking advantage of knowledge of the project and architectural parametric models and extends these to assist in the detail design development with sub-contractors. Once the design proposals are returned to the architect by the sub-contractors LRS illustrated how the parametric model can be extended to *check detail design*

Chapter 6

Stadium Seating Bowl Modeller

6.1 Introduction

This chapter reviews the process of developing a reusable parametric tool, the Seating Bowl Modeller (SBM). This is a tool for designing seating facilities in sports venues. The case study identifies a new task, developing reusable models and the associated considerations for the architectural parametric designer. Projects described in the literature tended to focus on parametric modelling of specific projects. Where descriptions of generic tools were identified they focused on the implications of the methods captured or applications of the tools rather than the development process. Primarily the development of a reusable parametric tool concerns knowledge capture. In this case study the tool described captures a set of well-defined recorded methods and the extensive experience of a group of expert designers.

The development of the SBM provides further insight into the key areas, identified in the literature review, that the case studies should seek to focus on. In particular are the contributions to the split opinions identified in the literature review, these include:

- Libraries of reusable tools.
- Completeness of problem description before starting parametric design.

- Parametric design as limiting breadth of exploration.

This case study provides practical examples of tasks identified in the theoretical literature but not illustrated in projects documented in the practical literature:

- Identifying parameters, initial values and valid ranges.
- Case retrieval (starting a design process with an existing design and adapting it).
- Seeking parameters rather than shape.

Additionally the case study provides further descriptions of the process of fragmentation and the use of multiple representations in parametric models.

6.1.1 Background

Work on the seating bowl modeller (SBM) began in March 2007. Following the successful implementation of parametric design on LRS, awareness of parametric technology had grown within HOK Sport Architecture (now known as Populous (2009) but referred to herein as HOK). As a result of this growth, a focus group, led by a practice Associate, was established to capture the process of seating bowl design in a parametric model. The author was employed as a consultant to implement this with Bentley Systems' GC.

The goal of the project was to capture and formalise standard methods used throughout the practice for designing seating bowls. Guidelines set out in various documents and by different governing bodies specify these methods. The primary source was The Department for Culture Media and Sports ”Guide to Safety at Sports Grounds” (HMSO, 2008). This was supplemented with guidelines determined by the Federation International de Football Association (FIFA) and the Union of European Football Associations (UEFA). HOK's own stadium design principles are published in ”Stadia” (John & Sheard, 2000). Chapter 24 of “The Metric Handbook” (Adler, 1999) provides a basic outline of the principles.

In addition to the published regulations and guidelines on best practice in the design of stadium seating, experienced bowl designers from HOK had developed further rules which had not been formally recorded. Instead, these were distributed in the minds and sketch books of a few architects. This project offered the opportunity to capture and formalise these rules along with the guidelines from the literature. The resulting model was intended for use by architects in the practice following some brief training.

Between May 2007 and January 2008, seven SBM development meetings were held. At the end of this period eight members of the practice were each given four hours of training in using the model. Since then the SBM has been extended and used in the design development of the London 2012 Olympic stadium seating bowl. It has been suggested (Parrish, 2005) that similar parametric technology was applied during the design process of the Bejing Olympic and Allianz Munich seating bowls. Explicit details of the methods applied for these projects have not been published.

6.1.2 Context

The parametric model aimed to capture a design process that is based around the definition of a section. This section determines the position of spectators eye-positions, each is dependant on the spectator in front. Manually this is a simple but repetitive drawing task. Before the widespread use of CAD within HOK, a seating bowl design would be developed by manually drafting sections and plans using drawing boards with parallel motions. Other than time saved through more efficient editing, the introduction of CAD packages initially had little effect on the seating bowl design process. During the early 1990s some seating bowl designers at HOK began to use a series of Visual Basic routines that parameterised the repetitive task of generating a seating bowl section within Microstation. These sections formed the basis of two-dimensional drawings which were elaborated with more manual CAD drawing techniques. Subsequently the office had not retained the computation skills required to maintain these routines. HOK wanted to develop more user friendly and dynamic versions of these routines that could be used for training new staff in the principles of seating bowl design. HOK also wished to extend the routines to produce three-dimensional models which would form the basis of two-dimensional drawings and visualisation models.

The shape of the seating bowl plays a significant part in defining the whole stadium (Parrish, 2005). Variations in the bowl have large effects on construction costs and quality of spectators views. When designing new stadium facilities, HOK's goal is "to get as many people as close to the action as possible" (Craine, 2008), ensuring the best possible atmosphere and experience for spectators. In the past, configuring the various parameters to achieve the best possible stadium has meant a great deal of time spent manually redrawing and remodelling designs.

6.1.3 Development team

The project was organised around a series of meetings between the author and a specialist internal team focused on developing a parametric seating bowl. The team consisted of three practice members considered experts in the task of seating bowl design. Cumulatively they had thirty years experience and it was this experience and knowledge that the process aimed to capture. These experts formed an advisory body that instructed and directed the SBM project. They explained the underlying principles of seating bowl design, including the subtleties of their own approaches based on experience and implementation of specific guidelines that designs must satisfy.

Two further members were included, architects from HOK who were inexperienced in bowl design experience but with working knowledge of GC. Their task was to master the parametric version of the process, and pass their knowledge on to other members of HOK. For these members participation in the team also presented an opportunity to become familiar with the principles of bowl design. The final team member was one of HOK's CAD managers. His role was to oversee the process and learn how to use the SBM. Eventually he would take responsibility within HOK for the SBM and support designers using the tool. The author's task was to develop and construct the parametric model through consultation with the team and then train other members of the practice in its use.

6.2 Overview of completed process

6.2.1 Seating bowl terminology

In order to describe the principles of the system the following terminology is used in this chapter.

c-value	vertical dimension from eye point of spectator to sight line of spectator on row behind (figure 6.1).
concourse	circulation area below and connected to seating bowl by vomitory.
eye-position	theoretic position of spectator's eye (figure 6.1).
focal point	nearest point of interest on playing field (typically on the side line for a football stadium)(figure 6.1).
front of seating bowl	planar curve indicating the boundary between pitch and seating areas (figure 6.2).
gangway	stepped access to seats through centre of spectator block (figure 6.3).
raker	centre line of sloping structure for support of bowl (figures 6.2 and 6.4).
seat-front	theoretical position of front of seat (figure 6.1).
seating bowl	the stepped surface onto which seats are located (figure 6.3).
sight-line	line from a spectator's eye to focal point (figure 6.1).
spectator block	area of seating, within which all spectators are assumed to enter and exit via the same point. (figure 6.4).
super-riser	large riser required to accommodate spectators in wheelchairs (figure 6.3).
tier	continuous section of bowl (figure 6.5).
vomitory	point of access from concourse to seating bowl (figure 6.3).

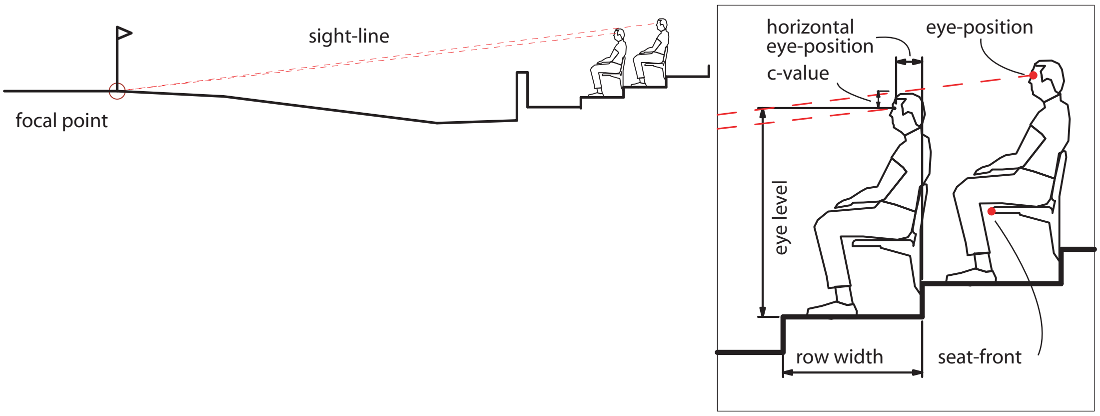


Figure 6.1: C-value method.

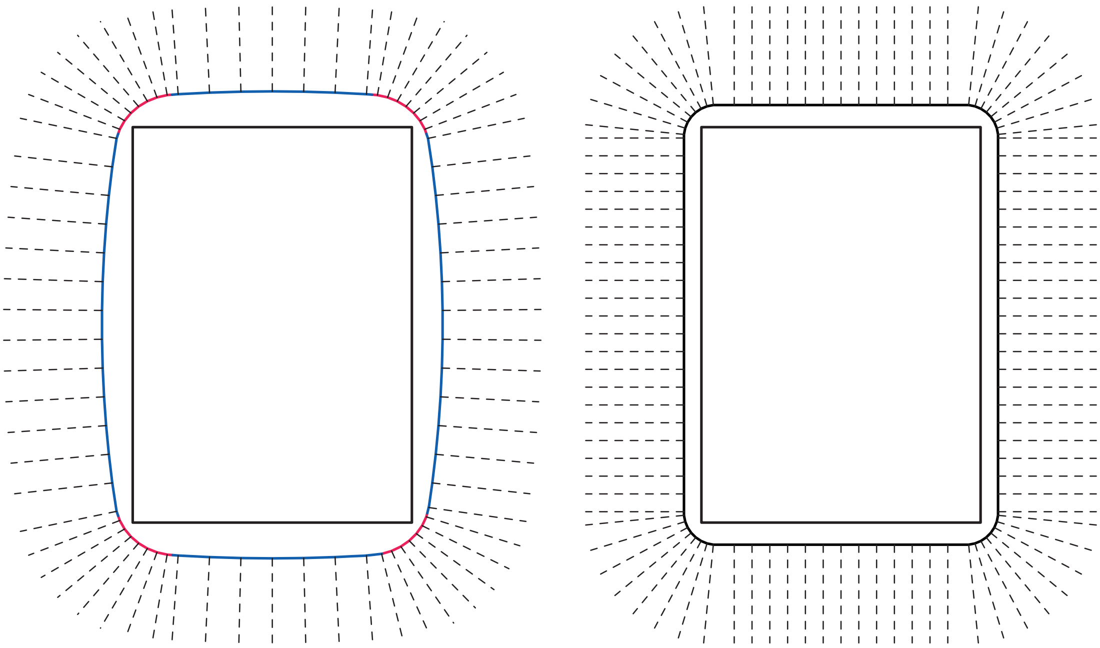


Figure 6.2: Front of seating bowl, arc based (left), rectangle based (right) and rakers (dotted).

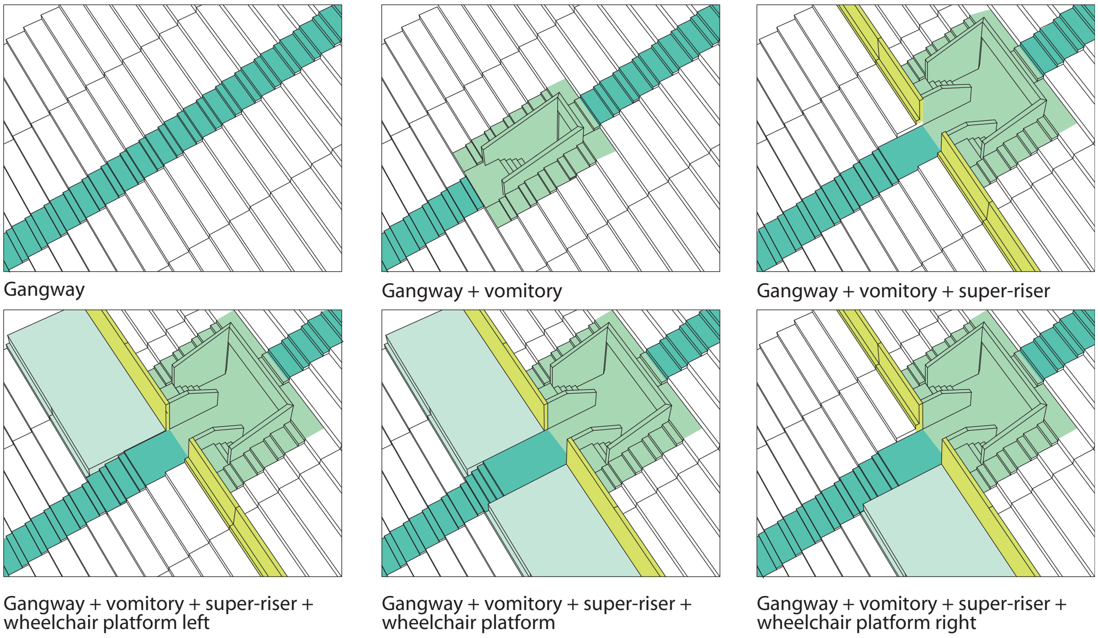


Figure 6.3: Seating bowl surface variants. Combinations of gangway + vomitory + super-riser + wheelchair platform.

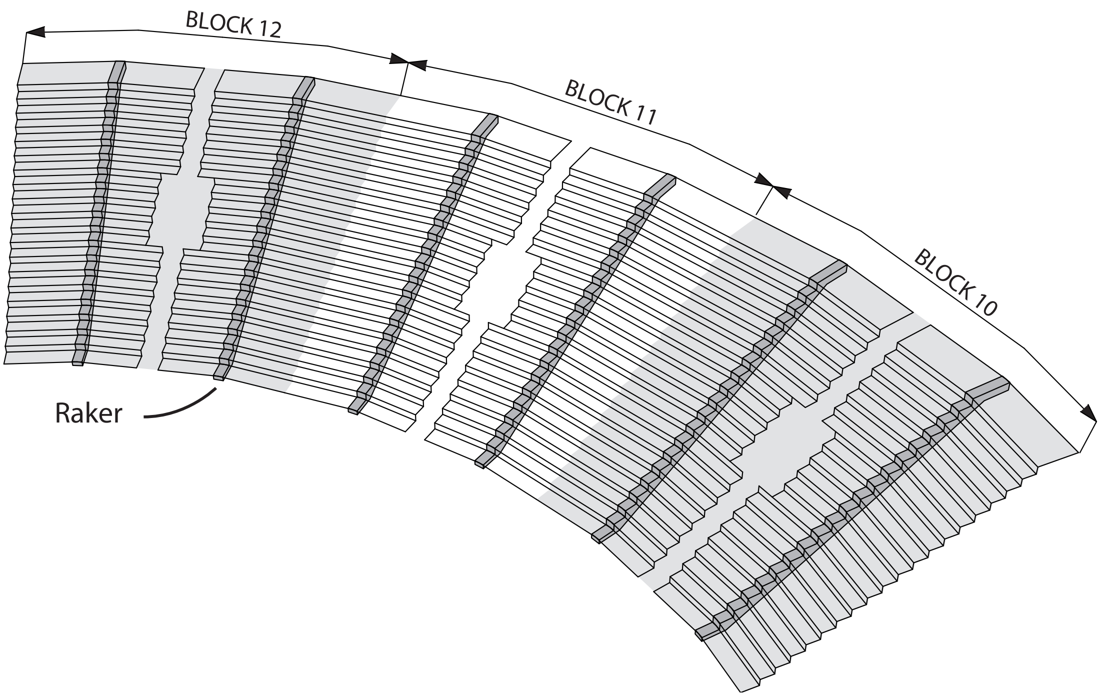


Figure 6.4: Relative positions of rakers, spectator block boundaries, gangways and vomitories.

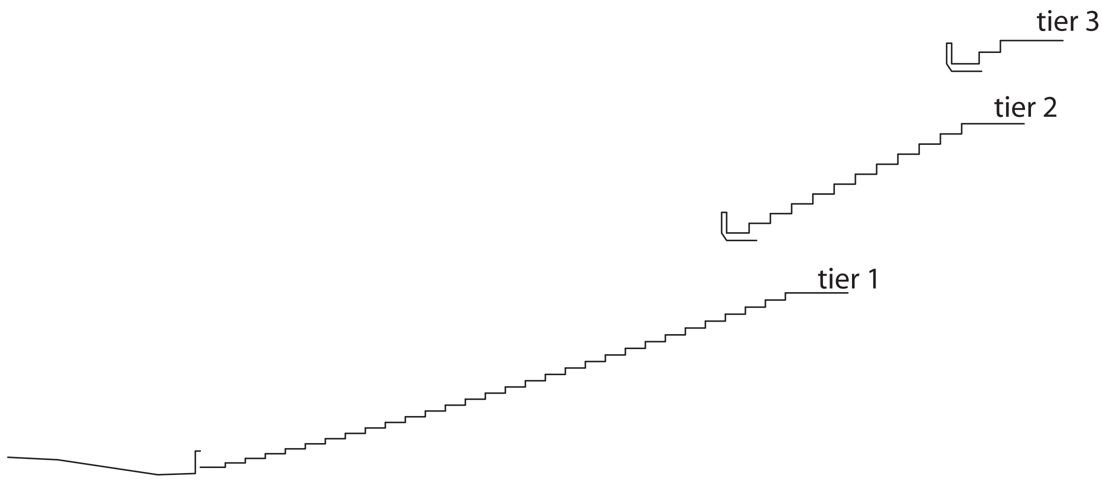


Figure 6.5: Seating bowl section.

6.2.2 The c-value method

The section used to define a seating bowl is generated using a parameter commonly referred to as the ”c-value”, and can be considered as a measure of view quality. The c-value is a vertical dimension between a spectator’s eye and the sight-line of the spectator on the next row (figure 6.1). Constructing a seating bowl section with this method requires an iterative calculation to locate spectator eye-positions. Typically this starts with the spectator in the front row. Using the eye-positions and offset parameters defining seated eye level, horizontal eye-position and row width, the surface of the seating bowl can be defined. A constant c-value will define a stepped section describing a shallow curve (figure 6.6). This section is effectively swept around the stadium to define the three-dimensional seating bowl surface. The two most significant factors in defining the seating bowl sections are the chosen c-value and distance between the focal point and first spectator. Figure 6.6 indicates the implications of changing these parameters.

6.2.3 Model structure

The model consists of two parts, a spreadsheet and a script file. The spreadsheet contains a set of parameters (initially with default values) and also functions as a container for extracted data such as seating capacity. The computer script file is a coded description of all rules and relationships. The first step in the script is to read all parameters from the spreadsheet.

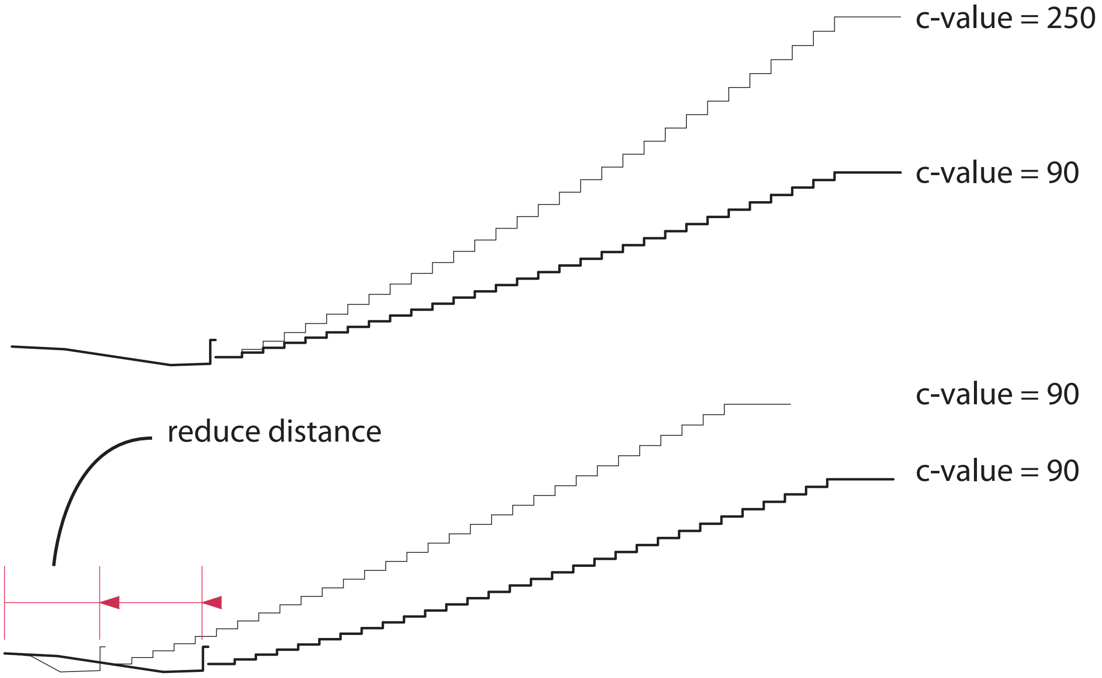


Figure 6.6: Change in section. Left: increasing c-value. Right: reducing distance from focal point.

Subsequent steps execute rules which combine with the parameters to define some part of the seating bowl.

6.2.4 Model function

The model is organised hierarchically, which reflects the process it captures. Depending on the level of design detail or desired output the hierarchy allows the user to run through functions and branch off into sub-functions (figure 6.7). Fundamentally the model involves generating a plan and section which are combined with evacuation requirements, provision of seating for wheelchair users and access to seats via gangways and vomitories. Based on this it is possible to calculate stadium capacity, analyse view quality and produce models to incorporate into other drawings and to form the basis of visualisation studies.

The process begins with the configuration of the pitch. Dimensions defining the pitch and its boundary conditions locate the front of the seating bowl and the position of the first spectator. Rakers are located perpendicular to the front of the seating bowl and spaced according to a specified structural bay size. The position of the first spectator is the starting

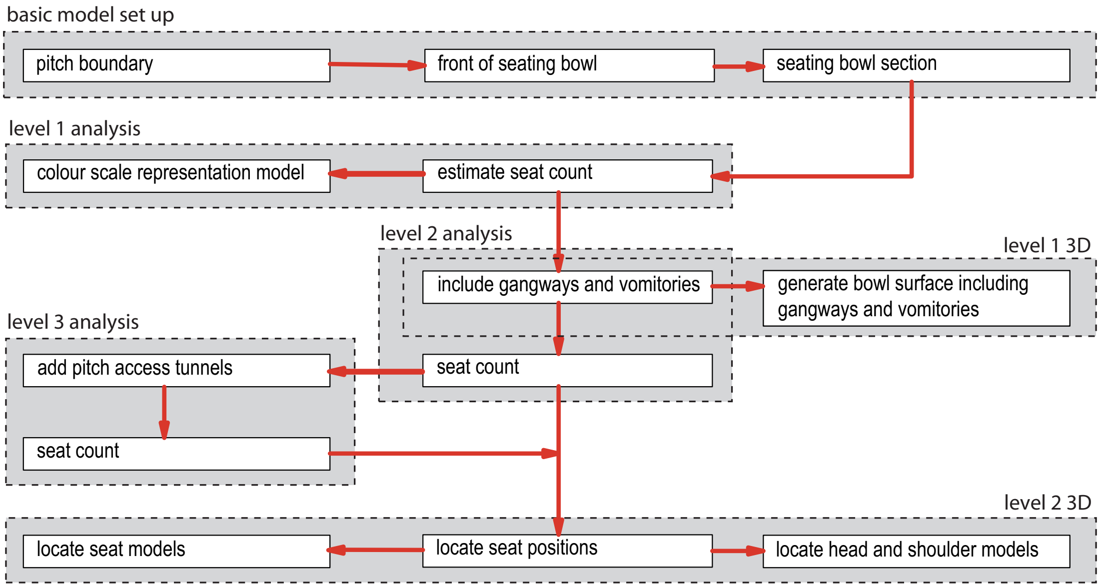


Figure 6.7: Functional overview of seating bowl modeller.

point for the section definition. The c-value method is applied for a specified number of rows to define the section.

Multiple tiers may be specified, which are set out based on the position of the last row in the tier below. Within any tier it is possible to accommodate a spectator in a wheelchair. A series of rules dictate the geometry of the section to provide the wheelchair user with a c-value that is as least as good at the surrounding seats.

The section used to define the seating bowl provides a constant c-value for a specific distance between the focal point and the first spectator. This distance varies around the stadium as the gap between the pitch edge and the front of the seating bowl varies. The result of this is that the c-values are not constant around the stadium. The range of c-values can be represented as a set of coloured surfaces (figure 6.8).

To generate this representation the theoretical eye-positions around the whole stadium are joined in a series of straight lines, faceted between rakers. The c-value can be calculated for each facet of each row. Using each c-value, a corresponding colour value can be calculated and is assigned to a surface which represents the quality of view at that location. Repeating this round the seating bowl defines a three-dimensional model that represents the range of quality of view around the stadium.

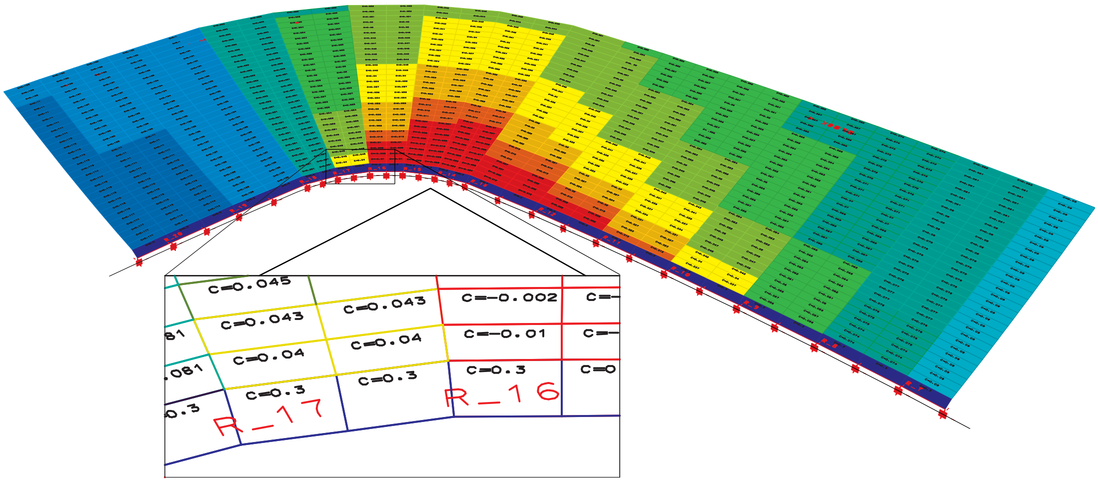


Figure 6.8: Colour scale representation of bowl.

In a similar way as the eye-positions the theoretical seat-front positions around the stadium can be defined as a series of straight lines, faceted between the rakers. Dividing the total length of these lines for each row by the seat width gives a number of spectators per row, repeating this for every row gives an initial estimate of stadium capacity.

To produce a more accurate value for stadium capacity, gangways and vomitories need to be considered. Around the stadium a series of spectator blocks are defined (figure 6.4). In the centre of each block is a gangway and possibly a vomitory. Within the block, all spectators are assumed to enter and exit via the gangway / vomitory. The width of the gangway / vomitory is a function of the number of spectators in the block and parameters defining pedestrian flow rate and maximum evacuation time.

Determining gangway and vomitory width begins by calculating an initial count of spectators in one block. This is achieved using the length of seat-front lines and subtracting a default width of the gangway / vomitory. This figure is divided by the seat width to give the number of seats per row. Repeating this for each row within one spectator block gives the number of spectators in that block. This value is then used to determine what the gangway width should be. Gangway width affects the number of spectators in one block. The calculation is limited to twenty iterations or it stops when the width converges. The width is also rounded to the nearest twenty-five millimetres, the width generally converged within the twenty iterations. Spectator block capacity and gangway width are recorded in the spreadsheet.

Once the positions of seats are known pitch access tunnels can be located in plan. Seat positions conflicting with tunnels are removed and total seating capacity re-calculated. Reference geometry such as seat objects and head and shoulder silhouettes are optionally located at each seat position (figure 6.9).

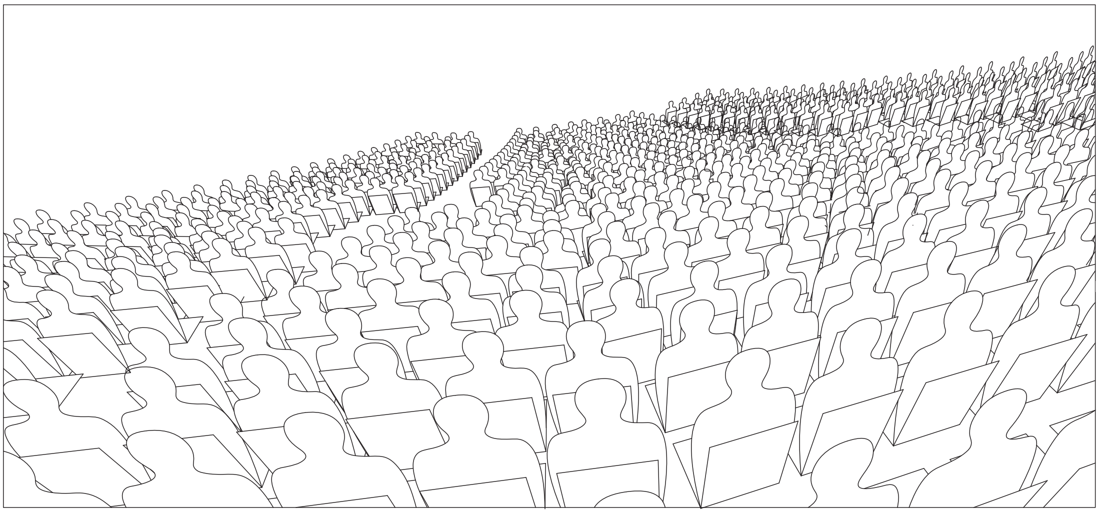


Figure 6.9: Seats, heads and shoulders located on bowl model.

The seating bowl section defines lines representing the seating bowl surface. By locating a section at each raker position a surface model can be created by ruling between sections. Where gangways and vomitories occur surface geometry is generated that represents stairs and walls (figure 6.3).

6.3 Analysis

The SBM case study contributes to the objectives of this thesis by identification and illustration of a parametric task concerned with developing reusable tools. The differences and similarities between this task and others previously identified are described. Analysis and observations of the case study provide practical examples that illustrate and suggest a set of considerations that, if taken into account, will help when tackling this type of task. Potential architectural applications are anticipated across a range of scales from building elements to routines for developing design details. In the task description and related considerations the case study proposes a framework for tackling these.

The task of developing reusable tools involves parametrising a set of rules and designer knowledge. These are captured within the model in way which is designed for future use and further extension. The SBM illustrates that knowledge capture is a sub-task of the developing reusable tools task. In this case study, knowledge capture was observed to proceed on a trial and error basis. This was necessary in order to interpret verbal descriptions of experience and to identify the full extent of the methods required to design seating bowls. Parametric model development for this reusable tool is described as proceeding following the three iterative steps *Propose-Critique-Modify* (PCM) that had been defined in the literature as a design method.

Analysis of the SBM case study provides an opportunity to address several of the key areas defined in the literature review. These include the split opinions and critique, providing examples of theoretical tasks and further illustration of tasks.

The first split opinion this case study analysis addresses is the use of libraries of reusable tools. The SBM demonstrates how a library of tools of a larger scale and more extensive functionally than those described in the literature could exist. The case study proposes that an accompanying library of parameters may also be required to work with tools of this scale.

Contradictory views were conveyed in the literature regarding the level of completeness of problem description and the initiation of parametric design. The SBM contributes to this in two ways. Firstly it demonstrated how knowledge could be parametricised by constructing models that were a mixture of assumptions and complete descriptions of rules. Secondly the model was structured in a modular and hierarchical way that enabled modules to be replace or updated as more complete functional descriptions became known.

Parametric design was criticised as limiting breadth of exploration as a result of the complex internal structures of the models, the time taken to construct and the time taken to update them. The development process of the case study indicates that the restructuring of models is an integral part of the design process and that it should be considered as an essential procedure when creating any parametric model. At a global level restrictions to breadth of exploration can be avoided through intelligent model structure. Intelligent structuring of the finished model can provide users with control of progressive levels of detail. This can minimise update times by preventing unnecessary complexity.

Three tasks were identified in the literature that have not yet been illustrated with practical examples. The first, *identify parameters, initial values and valid ranges* is demonstrated by the PCM knowledge capture process which was based around extensive discussion at development meetings and subsequent model modifications. Secondly, case retrieval, is illustrated by the use of a parameter library of built and typical stadiums. The SBM involved an initial pursuit of seating bowl form rather than more robust and generic rules. The later difficulties that this presented demonstrate that the theoretical literature was correct in suggesting seeking parameters rather than shape.

Finally, analysis of the case study provides further examples which emphasise the importance of the role of fragmentation and multiple representations in parametric modelling.

6.3.1 Task identified: developing reusable tools

The practical literature indicated that some parametric designers were concerned with developing reusable tools. However, the limited discussion of these relative to the body of literature suggested minimal significance. In the literature analysis it was therefore not possible to identify this as a parametric task. In the realm of engineering it was implied that having a set of bespoke tools was standard protocol (Sharma, 2008; AKT, 2008) and that dealing with procedures that could be generalised was more common than in an architectural practice. These tools tended to be concerned with rationalisation and analysis of existing designs. Successful applications were mentioned, but there was no discussion of the process of developing these tools. Within architectural practices the only mention of a reusable tool was a theatre seating analysis tool (Dritsas & Rafailaki, 2007). Again the discussion here was not of the tool development but of the translation of metrics of human perception into parametric models.

The SBM case study provides substantial evidence to suggest that the development of reusable tools should be considered as a parametric design task. It is proposed that there are several processes in design offices that could be captured as reusable tools. These could cover a broad range and scale of tasks spanning from stadium seating facilities (as described in this chapter) to parameterising standard building types such as apartments, offices or internal spaces. The range would also include the type of rationalisation tools briefly identified in the literature review found in engineering offices.

The case study demonstrates that the parameters that define a reusable tool can be a mix of building regulations, guidelines defined by institutions and experience based informal methods that are specific to a designer. In the case of the SBM the set of rules captured is described briefly in the sections above. A full description of the logic incorporated into the model is beyond the scope of this thesis. The detail and extent of logic captured by this model demonstrates an extensive functionality, this is a result of the scale of the design task it parameterises. However, the observations made from this case study are considered to be applicable to reusable tools capturing other scales of design task.

The SBM indicates that the task of developing re-usable tools shares some similarities with the task of creating a model which has previously only concerned developing a parametric model for a specific project (one-off tool). The need to develop a problem description, start the process, externalise ideas, translate design intent and develop a control system are common objectives for developing both one-off and reusable tools.

Reusable tools differ from one-off tools by the decision that instigates their development. The development of a reusable tool begins when a decision is made to capture a set of operations that are commonly repeated in many design processes. The development of a one-off tool occurs at a certain point in the design process of a project and assists in developing design ideas or captures a series of sequences that generate a specific design. The generic nature of the reusable tool places more emphasis on ensuring the rules are captured correctly and they are captured in a way that enables use by others and later extensions.

6.3.2 Considerations: developing reusable tools

When undertaking the task of developing a reusable tool the SBM case study suggests that the following items be considered.

- Develop a logical common language for variable and object naming.
- Develop the model in a modular or fragmented way to simplify extension and changes.

- Develop default parameter sets.
- Establish who is going to use the tool and what their skill levels are.
- Establish who is responsible for maintaining the tool.
- Establish who is responsible for managing the tool within the practice.
- Allow time for developing a user manual and documentation.
- Allow time for training users.
- Allow time for modification following training.
- Allow time for longer term support.

Parameter names defined for the SBM are based around a logical common language. This terminology was developed as a result of the language used by the experienced seating bowl designers during the development meetings. It was important to identify the existing naming system and extend this to include further parameters that previously had not been given a name. A system of naming in the model was adopted that involved taking the original names and concatenating words using a method commonly referred to as camel case (Microsoft, 2009). Where appropriate, words were shortened to simplify the number of syllables but retaining the original meaning. Shortening made reading and writing quicker while concatenation was essential within the parametric scripts because variable names cannot contain spaces.

The manual design methods captured by the SBM are fragmented, which is reflected in the modular structure of the model. Figure 6.7 illustrates this modularity and the benefits are described in the sections below.

Understanding who would use the SBM was crucial in the design of the model. The primary users were present in all the development meetings and were involved in testing the model as it developed. The feedback from this was essential in developing the model in a way which suited its intended users. For example, feedback indicated that introducing new users to the process of seating bowl design was easier when they could dynamically manipulate parameters and observe the changes on screen. The use of the spreadsheet as a parameter record and input format was found to be too complicated for novice users. This complication was thought to be a result of the additional layer the spreadsheet added and made control of the system a more abstract task.

Feedback also indicated that experienced users often only required a model to define a two-dimensional section. The implication of this was to develop two models in parallel. One model had the capacity to develop the section alone and a second model included the full three-dimensional functionality.

Establishing who the users were and understanding their experience with the software indicated that all the scripts should be managed and maintained by the author. Throughout the development process the script had been carefully commented with the intention of sharing. Despite these efforts the author was the only beneficiary. The documentation within the script provided valuable help when returning to modify, improve and extend the model several months after it was created. Maintaining the model is an ongoing process and continues at the time of writing. New projects reveal aspects of the model that have not been fully tested, require refinement or new modules that need adding.

From the outset of the project one of HOK's CAD managers had been part of the development team. His task was to learn the design process, develop a working knowledge of the model and also to be responsible for managing it within the practice. He later also became the primary user in HOK and developed a series of parameter sets for recreating some of HOK's successful existing bowl designs as starting points for new designs (these are discussed later in this chapter).

A full manual was developed for the model. This included a step by step tutorial in using the model, listing of all parameter names along with a brief description, references to cell location in the spreadsheet and to diagrams that related parameters to the part of the model they controlled. Using this manual, training sessions have been held both with participants of the development team and other architects from the practice. These sessions provided feedback on the user manual and the model itself which were subsequently incorporated into both.

6.3.3 Knowledge capture

Chapter two identified the importance of the role of knowledge, experience and heuristics in the design process. Primarily this was described as a way of reducing the size of a solution space by applying some structure or constraint on the problem based on rules of thumb. The SBM case study provides a practical example that confirms this observation. Experience and knowledge of the expert bowl designers was incorporated into the model as default parameter values and geometric logic, which reduced the range of possible configurations.

Methods for capturing and incorporating knowledge into parametric models were not referred to in the literature. On the basis of this case study it is suggested that knowledge capture should be considered as a sub-task of developing reusable tools. This sub-task is similar to capturing design intent, a sub-task of the translation task identified in the literature. However the two sub-tasks differ in their levels of specificity. Capture of design intent concerned specific projects, whereas knowledge capture is concerned with broader experience that can be applied to multiple projects and this presents further challenges.

In the case of the SBM, knowledge capture proceeded as a process of interpretation of verbal descriptions given by the expert designers of their experience. The challenges of this process can be understood in two areas, language used and the extent of the knowledge that the SBM aimed to capture. Language was challenging because of the differences between the terminology used by the author and the expert designers. Language used by the expert designers reflected the time spent working on this building type and use of working methods based on recalling chunks and snippets of previous drawings and models and adapting them using traditional CAD methods. These methods did not necessarily reflect the process required to develop the parametric model there were subsequent misunderstandings. The level of detail and intricacy of the model often meant that rules, parameters and processes were sometimes overlooked in discussions. Subsequently, when constructing parts of the model, assumptions had to be made about certain rules and parameters. These assumptions would usually be partially correct but could be corrected when the model was demonstrated to the development team.

An example of the difficulties resulting from language is the use of the term ”elliptical” by the expert designers. To the author this meant a geometric object with a clear mathematic definition. Work was undertaken to add a module that defined an elliptical front-of-bowl-curve. However when this was presented to the team it became apparent that the term ”elliptical” was used to mean a curve constructed from eight tangent arcs that approximate an ellipse (figure 6.10). The reason for this can only be understood with experience of

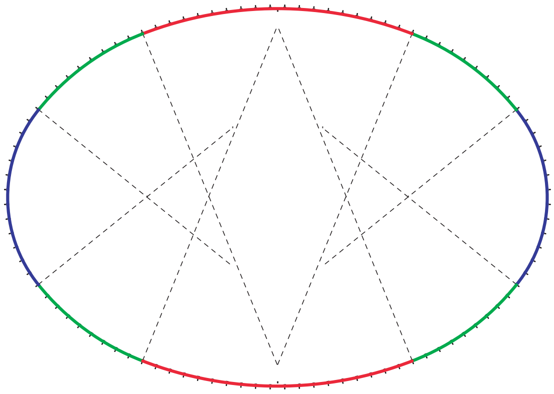


Figure 6.10: Elliptical seating bowl, defined with tangential arcs.

designing seating bowls and relates to a rational construction strategy. The seating bowl is constructed of straight pre-cast concrete elements supported by rakers. When the front of seating bowl is defined as a curve the concrete elements form facets approximating the curve. If an elliptical arc is approximated with a series of equal length straight lines the angles between each facet vary. When a circular arc is subdivided in the same way the angles between facets are constant. When producing the pre-cast elements a constant angle is a financial saving as it minimises the construction of form work. This practical reason explains why expert bowl designers produce “elliptical” seating bowls that are approximated with circular arcs.

Overlooking the explanation of the detail, underlying the elliptical problem is an example of the author making an incorrect assumption in order to try and achieve results. Another case of this involved a verbal description of how to locate the eye-position of of a spectator in a wheelchair. This method was described extensively and involved locating the eye-position a spectator standing in the row in front of the wheel-chair (figure 6.11 top). The eye-position of the spectator in a wheel-chair was defined using the standard c-value method and the standing spectators eye-position. After developing and demonstrating a model for this system it was revealed that a second method existed which was preferred by some expert designers. The second method involved taking the spectator in front of the wheel-chair and finding their sight-line. This sight-line was then offset to pass through the standing eye-position of the spectator in front and define a new focal point. The new focal point, the standard c-value method and the standing spectators eye-position was then used to locate the wheel-chair eye-position (figure 6.11 bottom). This aspect of the model was revised, a switching parameter was added so users could select between the two methods.

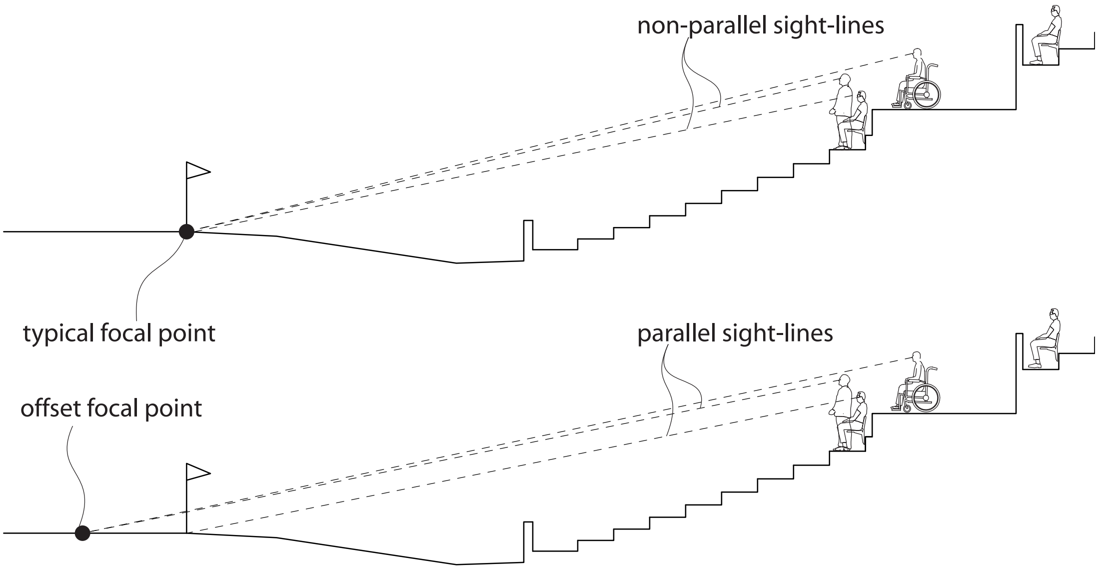


Figure 6.11: Wheel-chair eye-positions. Top - standard method. Bottom - parallel sight-line method.

A further example of omitted detail involved the conditions at the edge of the pitch that determine the eye-position of the first spectator. Extensive discussions informed the construction of a model (figure 6.12 top). This was demonstrated to the development group, at this point a further method for defining the position of the first spectator was described. This time the boundary condition included a hoarding for advertising specified for all UEFA stadiums (figure 6.12 bottom). The top of this hoarding defined the sight-line of the first spectator. The model was reconfigured to reflect this, and a switching parameter was added so users could choose which of the two methods to use.

These examples were typical of the development process. The way in which the model developed can be understood as following a sequence of PCM. PCM was described in the literature as a process for tackling design tasks involving generating and evaluating a design and subsequently adapting the design or the system that produced it. The SBM demonstrates how the PCM design sequence is also applicable to the development of a reusable model. Based on assumptions and interpretation of the verbal descriptions given by the expert designers a model would be proposed. It would then be critiqued at the following team meeting, criticism would reveal incorrect assumptions and would lead to

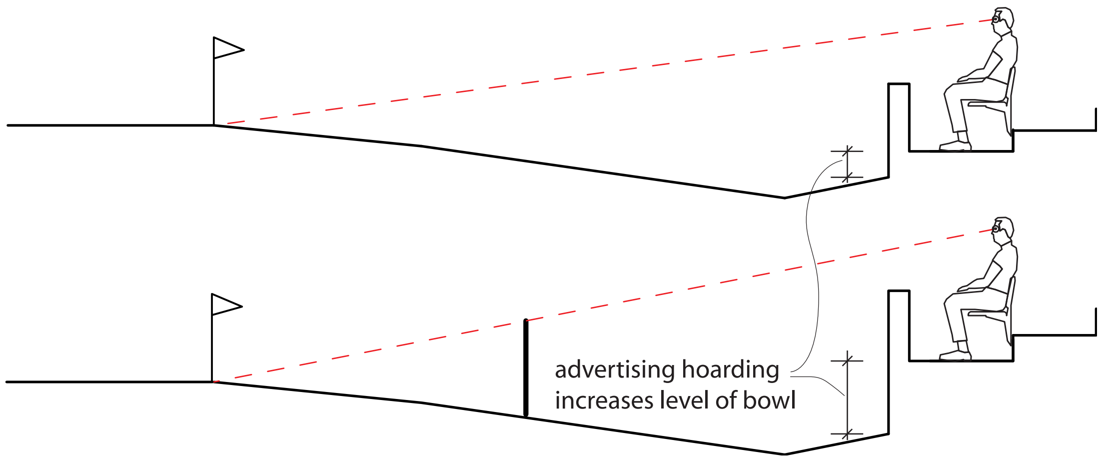


Figure 6.12: Pitch edge condition. Top - standard method. Bottom - including advertising hoarding.

further details and alternative methods being revealed. The model would be modified to reflect the critique and the modifications demonstrated at the following meeting.

6.3.4 Libraries of reusable parametric tools

One area which the literature review found contradictory views was the use and development of libraries of reusable tools. Theoretical literature suggested libraries of abstract parametric models could be used by designers to select starting points or establish methodology for design tasks. Practical literature indicated that developing highly specific tool sets was common amongst parametric designers operating independently or within engineering firms. However, the task of developing these was not discussed. In architectural practice libraries were described as a possibility but projects were also seen as too varied to benefit from the effort required to make a library.

The SBM contributes to the set of contradictory view points in several areas. The SBM is a tool type not described in the literature, a parameter library to accompany this tool type is proposed and a generic framework for tackling development of reusable tools is suggested.

Reusable tools of the scale, specificity and functional extent of the SBM do not feature in the literature on reusable tools. It is on the scale of an entire building and applicable to a single building type. As a result the rules that the SBM uses are very specific and the functions that the model provides are extensive. It is proposed that larger scale building elements may become the focus of parametrisation activities and the observations of the SBM may be valuable in developing these.

On a superficial level stadium seating bowls all appear very similar. However, the experience of a spectator at a live event within a stadium suggests that certain seating design characteristics will provide a better or worse spectator experience. HOK's most successful seating facilities have been analysed and defined as sets of parameters which can be used to establish a design using the SBM. In addition to built stadiums, several other generic parameter sets have been defined based on typical configurations (figure 6.13).

Figure 6.13: Four typical seating bowl types.

These parameter sets form a library that a designer can select from to use as a starting point for the design of a new stadium. Libraries of parameters were not discussed in the literature. It is proposed that if a practice develops larger scale building elements as part of a library these would be accompanied by a library of parameters. The parameter library would be used to choose starting conditions which would then be adapted to the new context. The parameter sets can be based on previous successes and would allow solutions to develop quickly.

The literature indicated that many architectural design tasks were too specific to warrant attempts to generalise the parametric methods used. However, it is suggested that in fact there are architectural design tasks involving knowledge and published regulations of varied scales. These could be parametrised and to do so would benefit the practice undertaking this. The benefits that the SBM illustrates are to formally capture experience, incorporation of detailed regulations into models to prevent them being overlooked, reusable models can be used to train others, parameter libraries provide a way of storing and capitalising on previous successful designs and substantial time savings can be made. The development process of the SBM has been used to identify a generic framework for tackling such design processes.

6.3.5 Completeness of problem description

In the literature review opinions on the completeness of the problem description and the point of application of parametric methods were contradictory. Some argued for complete understanding of the problem before involving parametric design, whereas others proposed problem descriptions could develop as part of the process of producing a parametric model.

The SBM provides practical evidence to support the latter argument. This can be demonstrated at two levels. First on the level of capturing the rules and knowledge relating to specific parts of the model and second in the modular structure and functional hierarchy of the model.

Specific parts of the SBM model required descriptions of rules and relationships at high levels of detail. Section 6.3.3 on knowledge capture describes this. The approach taken was described as propose, critique and modify (PCM). This approach was necessary, as descriptions of the rules given by the development team were sometimes incomplete and assumptions had to be made. This is an example of commencing a parametric design task with an incomplete problem description. Assumptions were used to define a complete model which could be demonstrated to the team who would critique it and it would be subsequently modified. In this way the problem description and the model could develop simultaneously.

The modular hierarchy of the SBM allowed functional place holders to take the place of a module with incomplete description. Later these were replaced when a more detailed description became apparent. The clearest example of this was the module that functioned to define a front of seating bowl. In early stages of the model development this could define two types of geometry. The first, a system of eight tangential arcs and the second based on a rectangle with filleted corners (figure 6.14). The output of this module was a closed loop of faceted line segments which approximated curved parts of the front of seating bowl. When developing the model the possibility of defining other types of front of seating bowl was not considered, it was not part of the original problem description. However after the initial model was completed it was applied to other stadium types and found to fail when no-corner, circular or elliptical [1] configurations were required (figure 6.14). The original rectangle and tangential arc systems operated as place-holders until a more complete description was defined. At a later stage this module was replaced with others that could define the circular and elliptical stadium types. Later the elliptical system was further refined with the addition of a simple geometric solver to find a solutions which defined equal bay widths on all tangential arcs. The modular nature of the model meant that developments in problem description were simple to implement.

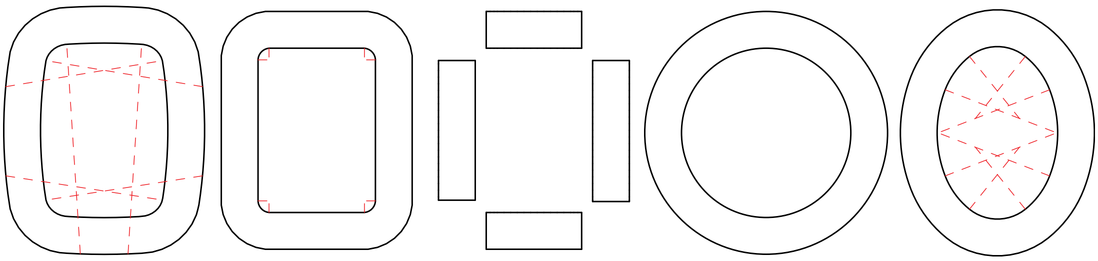


Figure 6.14: Seating bowl types. From left to right: tangential arc, rectangular, no-corners, circular and elliptical (tangential arc).

6.3.6 Parametric design can restrict breadth of exploration

Parametric design was criticised in the literature review for limiting breadth of design exploration. The reasons given in the literature for this limitation were the hierarchical structure of parametric models and the time taken to make changes to models that deliver high levels of detail.

Producing a parametric model with well defined hierarchy requires a lot of effort. This structure facilitates producing design variants with high levels of detail. However, if a designer wants to re-structure the model and therefore redefine the design under exploration, more effort is required. The literature described this effort as restricting the breadth of exploration, because designers are not willing to make the effort to change the model.

[1] To minimise construction costs elliptical seating bowls are approximated with tangential circular arcs.

Parametric models that produce high levels of detail can suffer from long chain dependencies. A long chain dependency refers to a situation where many objects in a model are linked together. When changes are made to such a model, updates can take a long time, even on fast modern computers. The greater the detail produced, the higher the number of linked objects and the longer the chain of dependency. The literature suggested that these update times were likely to prevent certain changes being made.

The case study demonstrates that the assumption that models will not be re-structured is incorrect. The SBM shows that for parametric modelling to be of most use, changes to the structure of the model are essential in the development process of the model and during its use. In the course of developing the SBM the model was re-structured several times. It is proposed that re-structuring of models should be anticipated in all parametric design tasks.

The modular structure of the SBM avoided the problems of long chain dependencies as it allowed the user to progressively increase levels of detail and to define a specific area of study. Users could choose the extent of detail by running selected modules (figure 6.7). Alternatively, parameters could be set to focus on either a set of, or an individual seating block within a single tier. Modules could also be exchanged for alternatives such as the front of seating bowl described above.

6.3.7 Identifying parameters, initial values and valid ranges.

The tasks of identifying parameters, initial values and valid ranges were identified in the theoretical literature. The SBM provides a practical example of these tasks taking place. The development process of the SBM was organised around team meetings. At these meetings parameters were verbally described, a model would subsequently be developed, and demonstrated at the following meeting. Models would be critiqued and then further modifications made. In this way parameters were identified. Parameter values were also discussed, some could be taken directly from the regulations governing seating bowl design. Other values for parameters not specified by regulations were debated in these meetings. Use of a particular value would be a matter of preference based on the experience of an expert designers. These debates played an important role in the development process. Although the model was parametric and parameter values were expected to change, knowing valid values was essential. The debates revealed both legal values and indicated their valid ranges.

6.3.8 Case retrieval

Descriptions of the task of starting a design process in theoretical literature suggested that design could start with case retrieval. Case retrieval was described as finding a complete design that partially suits the current design task and then adapting it according to the new context. The SBM is an example of a parametric system that is designed to be used in this way. As previously described, the users at HOK developed parameter sets that describe specific built stadiums and generic types (figure 6.13). These form a library of cases from which a designer can select one. The selected parameter set can then be adapted to suit the new context.

Use of the library of parameter sets is an example of design ”action” amplification that was described in the literature review. Storage of sets of parameters is equivalent to the explicit space described as an amplifier. Backup was described as the process of going back to a previous design which would correspond to selecting a parameter set for a previous stadium bowl design. An amplifier described as recall was the way in which a previous design could be combined into a new model. For the SBM this would analogous to taking a specific sub-set of a complete parameter set. For example taking the parameters for the first tier at Wembley and redefining the upper tiers.

6.3.9 Seeking parameters rather than shape

The task of externalising ideas and constructing models identified in the literature review suggested that designers should focus on parameters rather than shape. The SBM illustrates the results of a process that is too shape-focused, rather then parameter-focused. This is evident by the need to modify the part of the model that defines the front of seating bowl. The original model included the ability to define a front of bowl based on tangential arcs. This later proved to be inadequate when trying to define circular and elliptical (approximated by tangential arcs) shaped bowls. Even though this should have been possible theoretically, the original definition failed for two reasons. It was based on a sequence of geometric operations which failed when all arc centres were coincident (circular bowls) and did not anticipate the range of arc radii required for the elliptical approximations. The original emphasis had been on defining a shape with four arcs (north, south east and west) with large radii, which were filleted at the pitch corners with smaller arcs. Subsequently the range of possibilities of eight tangential arcs was overlooked. If the parameters, rather than the shape of this system had been fully investigated, a single system could have been parametrised.

6.3.10 Fragmentation

Fragmentation was identified in the literature. It formed a key part of the underlying design theory. The SBM provides further practical illustration of this. The development process was highly fragmented. This was because the goal was to capture an existing fragmented design process. The fragmentation of the original process made each part easier to tackle, the same was true for the parametric model. When developing the model, each fragment could be broken into sub-parts which could be tackled independently and then later recombined. For example within the two-dimensional section, three sub-parts can be identified; the pitch edge, the standard c-value system and the positioning of super-risers within the section. Key parameters were identified (figure 6.6) which suggested a fragmented control system. The key parameters were controlled interactively while those having less effect on the geometry were stored numerically. This was particularly useful when introducing the model and principles to new users.

In use, the model operates as a modular system with the user choosing which or how many fragments they should implement (figure 6.7). Users can generate a basic model set up which defines pitch edge conditions, front of bowl curve, location of rakers in plan and a two-dimensional section (figures 6.2). Using these it is possible to get a quick indication of capacity. After this basic function the users chooses to progress into further levels of detail. Level one analysis generates a colour scale map representing view quality (figure 6.8). Level two analysis provides a more accurate seating capacity. Level three analysis requires tunnels to be configured and re-calculates seating capacity. The first stage three-dimensional model requires level two analysis in order to produce surface geometry of bowl, gangways and vomitories (figure 6.3). The second stage of three-dimensional modelling locates every seat and can insert a seat or head shoulder model at that location (figure 6.9).

Further to this functional fragmentation another organisational structure allows fragmentation within the model. The hierarchy of the built structure; seating bowl, tier, escape block, row, seat provides natural fragmentation. The user can specify which tier to generate and can select a group of spectator blocks to examine. Fragmentation on this level provides an opportunity to generate part of a seating bowl. This is useful because some sports venues such as baseball parks and race tracks do not require closed bowls. Selecting a small part of the stadium decreases processing time and proved useful in demonstrating how the system worked and for new users to develop a better understanding of how to control the model.

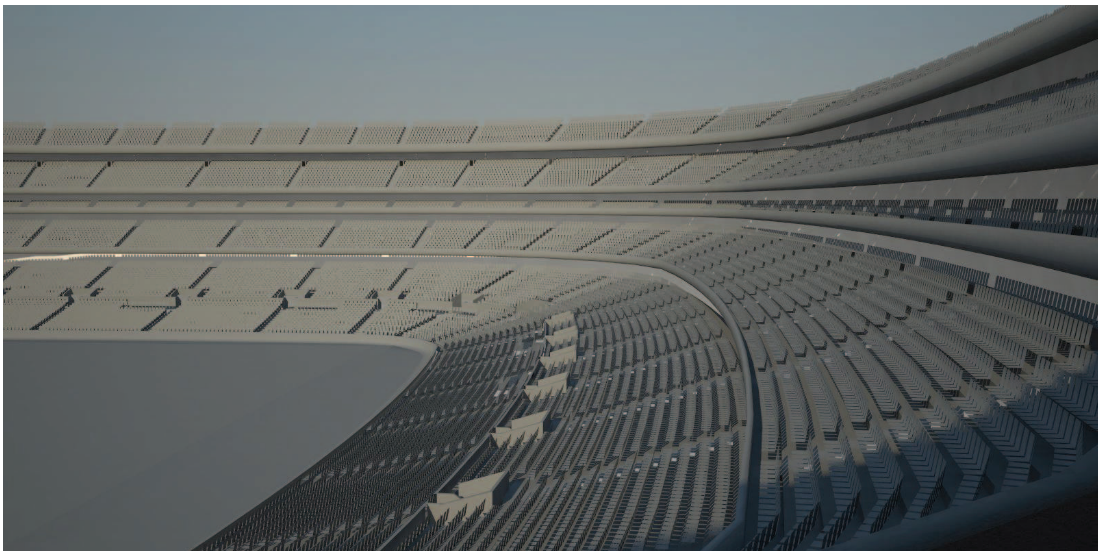


Figure 6.15: Visualisation of seating bowl.

6.3.11 Multiple representations

Multiple representations were identified as an essential component in parametric design. The SBM provides further practical illustration of this. Control of model is achieved via a numeric representation in a spreadsheet. These values configure geometry defined by relational characteristics that are represented as text in a script file. The representations produced numbers of spectators, two-dimensional plan drawings, section of stepped bowl (figure 6.5), plan of the structural layout (figure 6.2), organisation of seating into blocks all escaping via one vomitory (figure 6.4), three-dimensional seats and bowl and vomitories as surface models for visualisation (figure 6.15).

6.4 Summary

Figure 6.16 is a graphical summary of the contribution that the SBM case study makes to the objectives of this thesis. The primary objective was to identify the tasks the parametric designer is engaged with. The figure is the task structure diagram introduced in the literature review to illustrate the role of the parametric designer. Text and boxes shown in bold illustrate the areas that the SBM either adds to this structure or where it provides practical examples of areas identified in the literature review.

Analysis of the case study indicates a further task *develop reusable models*. This new task shares many similarities and sub-tasks with the create model task, and subsequently is shown on the task structure diagram as sharing the same sub-tasks. *Develop reusable models* was justified as a new task because of the expectation of repeated use and the generic set of rules it should parametrise. These have significant implications on the development process. Observations of the case study identified an extensive set of considerations, that if taken into account when developing reusable tools, will make the process more manageable.

The development process observed in the SBM was achieved through capture of the knowledge and experience of expert designers and published regulations. Knowledge capture is added to the task structure as a sub-task. The procedure that enabled the capture of knowledge was identified as PCM. Previously this had been described as a design method when using parametric tools but not as a method of developing the tools themselves.

The SBM contributes to the three areas of split opinion identified in the literature. As a reusable tool the SBM is on a scale and has functional extent that has not been described in the literature. Its proposed mode of use is as a part of a practice's tool set and it is suggested that the SBM is used in conjunction with a library of parameter sets. The SBM modeller provides practical evidence to support a theoretical view of parametric design as a process that can begin with incomplete description of a problem. This is shown both in the development strategy using PCM and in the modular structure of the completed model.

Parametric design was criticised as restricting breadth of exploration in the literature. The SBM challenges the basis for this argument by suggesting that making changes to model structure is essential during both model development and use. *Restructure model* is included

Task	Sub-task	Procedure	Practice example	Case study example
Create Model	Develop problem description	Assign function, structure, behaviour		LRS
		Identifiy parameters		LRS
		Fragment problem		LRS
		Propose-critique-modify		LRS
	Externalise ideas	Use library / memory		
		Case retrieval		
		Declare parameters rather than shape		
		Fragment model		LRS
		Multiple representations		LRS
		Propose-critique-modify		LRS
	Capture design intent	Translation	03 11 13 16 22	LRS
		Propose-critique-modify		LRS
	Rationalisation	Post-rational	06 09 11	
		Matching geometry	06 09 11 14	LRS
		Reduce geometry to simple elements	06 09 11 14	
		Flat panel	06 09 11 14 26	
		Pre-rational	05 07 08 21	
	Control	Design surface	02 12 13 15 21 22 28	LRS
		Fragmentation / hiearchy of control	21 12	LRS
Develop re-usable models	Develop problem description	Identifiy parameters		SBM
		Fragment problem		SBM
	Knowledge capture	Propose - critique - modifiy		SBM
	Externalise ideas	Declare parameters rather than shape		SBM
		Fragment problem		
		Multiple representations		SBM
		Re-structure model		SBM
				SBM
	Control	Fragmentation / hiearchy of control		SBM
	Implement in practice	Library / case retrieval		SBM
		Documentation		
		Training		
		Support		SBM
Design investigation	Find appropriate parameters and generate alternatives	Assign initial values		LRS SBM
		Reduce solution space using amplifiers		SBM
	Assess alternatives	Propose - critique - modify		LRS
	Generate and Test	Multiple representations to assess:		
		environmental analysis	11	
		structural	26 27	
		construction logic	22	LRS
		aesthetics		LRS
Construction documentation	Share information	Geometry method statements	FP	
		BIM models and external manager	FG	
		Static model files	SOM	
		External parametric with direct links to sub-contractors	DTP	
		Share parametric defintion		LRS
		Cross contractural boundaries		LRS
		Check detail design		LRS
Split Opinions + critique	Point of parametric application			LRS SBM
	Depth versus breadth			SBM
	Use and development of libraries			SBM

Figure 6.16: Seating bowl modeller summary.

as a sub-task of the *create model task*. Long chain dependencies associated with parametric design were also described in the literature as stifling breadth of exploration. Observations of the SBM suggest that parametric models can be constructed to facilitate progressive levels of detail which can limit the problems of long chains of dependency.

Practical examples of several procedures described in the theoretical literature can be observed in the SBM. Identification and assigning initial legal values was achieved through interpretation of extensive verbal descriptions of knowledge and regulations given by expert designers. The library of parameter sets that accompany the SBM illustrate how the design process can be started with case retrieval. Storing and recalling previous designs was identified in the literature review as a design amplifier which can reduce a solution space. The proposed parameter library functions as a store of previous designs which a designer would use to instigate or combine into a new design task. Declaring parameters rather than shape was proposed as a procedure of the externalise model sub-task. The case study demonstrates the implications of focusing on shape rather than parameters. These can be seen in additional modifications that were required once the model was in use.

The case study provides further practical examples of fragmentation in parametric design. This was observed in the description of the problem as it represented an already fragmented manual process. The SBM was subsequently structured in a fragmented way. The control mechanism was fragmented to provide different levels of control depending on the proficiency or needs of the designer. The SBM produces and is dependant on numeric, text based and geometric representations. This provides secondary evidence of multiple representations as a necessary component to parametric design processes.

The following chapter reviews a range of shorter case studies. These provide practical examples or supplementary examples that expand the descriptions of tasks, sub-tasks and procedures identified in both theoretical and practical literature. They also provide practical illustration of the remaining unfulfilled theoretical proposals that were described in chapter three but have not yet been observed in LRS or SBM.

Chapter 7

Further case studies

7.1 Introduction

This chapter summarises other cases studies undertaken by the author in the course of this thesis. Each provides insight into the key areas that the literature review identified for further examination. The introduction chapter noted how it was unlikely that every case study would involve material worthy of note, and that there would need to be some redundancy in order to find significant projects. The projects described in this chapter are those that after analysis are thought to make a significant contribution to the goals of the thesis, but not at a level that justifies an individual chapter for each.

The first three case studies summarised in this chapter are tall buildings; Blackfriars Tower (BLA), Moscow Tower (MOS) and Gazprom Tower (GAZ). These projects were undertaken shortly after the author began work on LRS. The geometric construction principle for each is thought to have originated in the methods used for LRS. This illustrates how memory of previous experience can inform later projects. In addition these projects also illustrate the procedures *rationalisation* and *reducing geometry to simple elements, hierarchies of control* and generating *representations to test construction logic and aesthetics*.

The next project summarised is Singapore Domes (SING). Unlike other projects described in this thesis SING used a purely code based approach to parametric design. This approach provides a counter point to the hierarchical approaches to control implemented with proprietary parametric software. The project illustrates the procedure of *matching geometry* at a late stage in design development. The model generated *multiple representations*, which were incorporated into architectural drawings, defined setting out geometry, initiated structural analysis and enabled structural design to be verified.

Several professional training sessions have been undertaken, these have also been treated as case studies. Content of these courses was coordinated around project specific questions which were given to the author prior to the training. Two independent experiences are summarised in this chapter illustrating several procedures in the task structure and contrasting parametric concerns. The first involved an architectural office and the second an engineering office. The architects were primarily interested in developing design ideas and required support with methods of geometric control, establishing team based workflows and automating information extraction from models. The engineer's concerns were further downstream in the design process and the focus was on methods for parameterising, rationalising and matching existing geometry.

Lastly the chapter reports on a series of introductory courses in parametric design with GC that the author has conducted during the course of this research. These have been held at Universities throughout out Europe and participants included academic staff, professionals and masters level students. The courses are short introductions and primarily aim to satisfy two objectives; develop technical skills specific to GC and introduce general concepts in parametric design independent of software platform. Originally the courses focused on these two objectives, however, it became apparent that this was often found to be too abstract and challenging by the participants. As the direction of this research developed the introductory course provided the testing ground for developing a practical exercise based on observations of the case studies. This exercise aimed to demonstrate key aspects of the parametric task structure identified in the thesis and illustrate abstract concepts in parametric design.

7.2 Blackfriars Tower

7.2.1 Background

Blackfriars Tower (BLA) is a mixed use high rise building on the south side of the river Thames in London (figure 7.1). Construction began in spring 2009. The project was undertaken with Ian Simpson Architects (ISA) and the author became involved during a planning enquiry. Geometry had been originally developed by consultants employed by ISA. Planners had rejected the original design and made recommendations for changes to the geometry. Success in the planning enquiry was dependant on these changes. ISA planned to implement the changes but wished to retain geometrical control in-house. They chose to use GenerativeComponents (GC) because it is based on the same CAD platform that their office already used.

Figure 7.1: Views of proposed Blackfriars Tower.

7.2.2 Overview of completed model

The methods used to define the tower geometry illustrate the procedure *reduce geometry to simple elements*. The implemented geometric method is based the method used for LRS and illustrates the author's use of *memory* of previous experience. Output from the model formed the basis of the architects two-dimensional drawing set and defined geometry that was used to set up visualisations which informed the planning enquiry. The implemented control system demonstrates a simple hierarchy of control where the model was constructed and managed by the author but parameters were defined by an architect. Parameter values were informed by guidance from the local planners, the sculptural aesthetics of the tower and internal floor areas.

The body and the top of the tower were defined as two different geometrical systems. The method of construction for the tower body prior to parametric modelling had been well documented. It involved five curves that define paths, along which circles were swept to create surfaces (figure 7.2). The surfaces were cut by a plane parallel to the ground at each floor level to create five planar curves for each floor. Straight lines then connect each of these meeting the curves at a tangent.

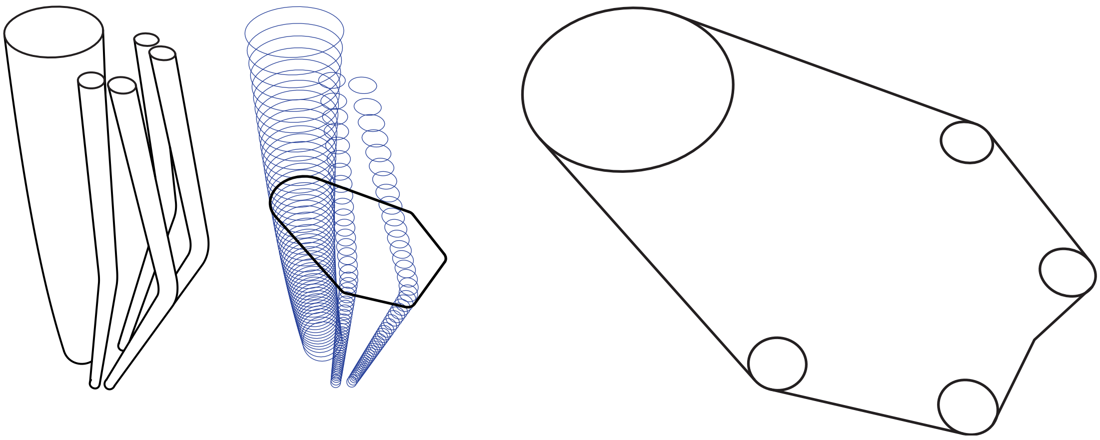


Figure 7.2: Original geometry method. Left to right, tubular surfaces, curves at plane surface intersection, floor plate.

This method was rationalised to involve simpler geometry. The paths of each tubular surface were retained. These defined control curves that could be manipulated graphically within the model. A plane for each floor intersected with the control curves to define a centre point of a circular arc. Arcs replaced the curves previously generated by surface plane intersections (figure 7.3). Parameters defining arc radii and floor levels were stored in spreadsheets.

The five arcs were joined with straight lines that met each arc at a tangent, defining a closed curve representing the floor edges. The tangent points on each arc could be calculated using trigonometric functions. Compared to the previous geometric method, the simplified version reduced that amount of construction geometry. Using circular arcs defined parts of the facade of the tower as sheared cones. This provided a close match to the original using a highly simplified method.

The floor edges were used to define a grid of points. The point grid formed the basis of two representations; construction of centre lines for mullions and surfaces representing

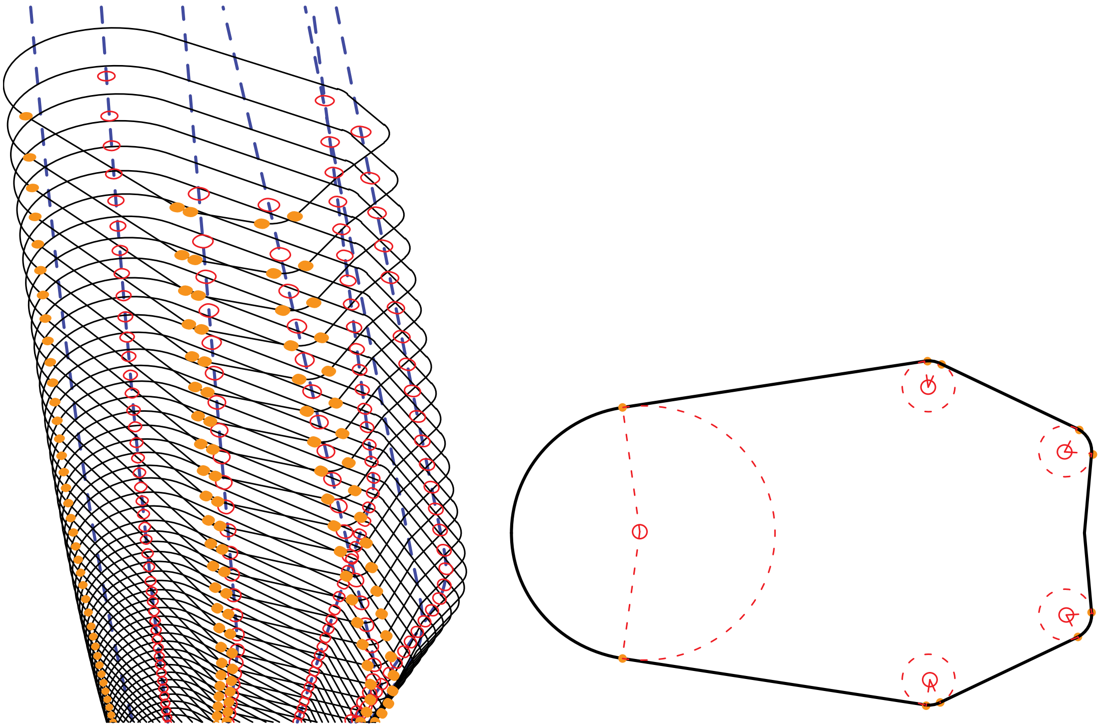


Figure 7.3: Control curves and typical floor. Left: control curves (blue dashed), arc centres (open red circles), tangent points (solid orange circles) and floor edges (black). Right: typical floor.

the glazing in each facade unit. Both were used in the aesthetic assessment of the design. The centre-lines were used in two-dimensional elevations several alternative facade grids were considered (figure 7.4). Surfaces were issued to visualisation specialists. Photo realistic renderings were required as part the planning enquiry (figure 7.1). Each glazed panel had to be individually modelled as the scheme specified varied glass finishes across the facade.

The facade grid also defined the position of two-dimensional mullions profiles around the edge of each floor. Every floor plan along with the mullion profile positions was extracted into separate model spaces as a Microstation file. This provided the basis for the architect's two-dimensional drawing set. By lofting the mullion profiles along the mullion centre-lines three-dimensional surface models were generated, these were used by the visualisation team.

The top of tower was dependant on the final three floors of the body of the tower. Each mullion centre line was extended up to an inclined plane defining the top of the tower (figure 7.5 left (blue dotted lines)). A third point was offset from the end point of the mullion centre-lines and in the inclined plan. Using the start and end of the extension and the third point a control polygon is defined. This was used to construct a planar bspline curve which was

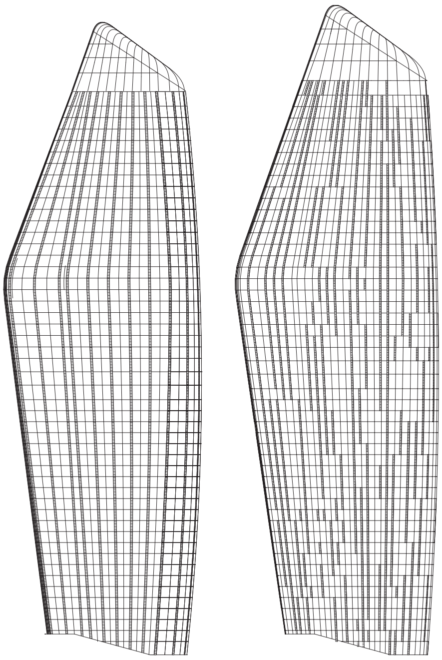


Figure 7.4: Two alternative elevations as line based representations.

tangent to both the mullion centre-line and the inclined plane (figure 7.5 left (red dashed curves)). The centre-lines of the mullions described the geometry of the top of the tower and were used in two-dimensional elevations (figure 7.4). These curves also define the path that the mullion profile is swept along to create a model of each mullion (figure 7.5 centre). The centre-lines were also used to create individual surfaces for each glazed panel of the facade which were used for visualisation (figure 7.5 right and 7.6).

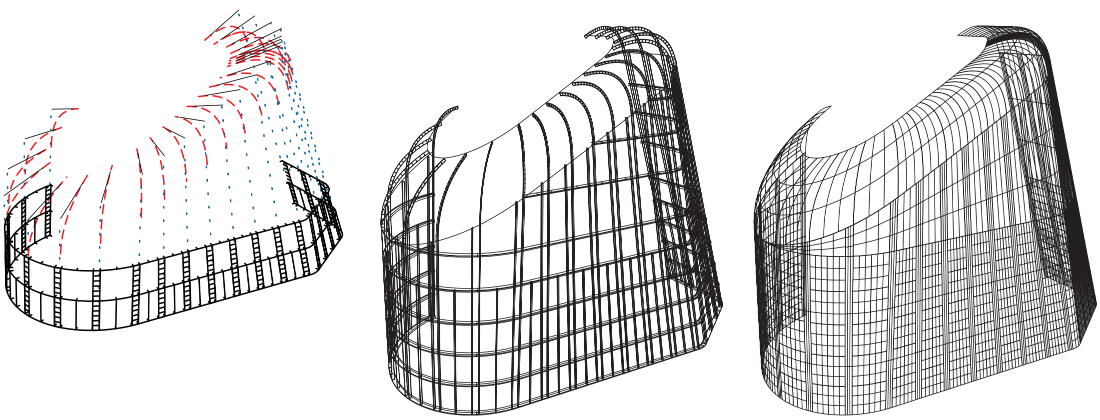


Figure 7.5: Construction of top of tower. Left : construction of control polygons and bspline curves. Centre: mullion model. Right: glazed panels as individual surfaces.

Figure 7.6: Top of tower.

7.2.3 Analysis

The problem was well defined at the point of parametric application both in terms of geometric method and design goals. The first parametric task was to implement a small geometry *rationalisation* which was achieved by *reducing geometry to simple elements*. In this case the curves that the floor edges were composed of were simplified from conics to an arc. The design goals were focused around changes suggested by planners and this meant the range of design investigation was limited to small geometric changes and facade treatments.

BLA uses a geometric method that involves defining planar curves that represent floor plates. Variation from floor to floor was defined by control curves. LRS geometry was defined with planar curves arranged vertically, these corresponded with structural sections. Variation between sections was also defined by control curves. The similarities between these methods illustrates how previous experience informs later work and ideas for construction models can be drawn from *memory*.

The parametric model for BLA was *hierarchical*. The author was responsible for construction and maintenance, while the control and definition of the parameters was the responsibility of ISA. The control system for the geometry had two *hierarchical* levels; the control curves for the tower could be manipulated dynamically on screen and numerical parameters were stored and defined in a spreadsheet. The control curves and numeric parameters were the first level of the model *fragmentation*. Control curves defined the geometry of the body of the tower which was the primary input for the top. The floor plates were the equivalent of a *design surface* for the body of the tower. All further geometry was based on offsets from the floor edges. Points around each floor defined a facade grid representing mullion centre-lines. Offsets from the facade grid defined the surface geometry required for visualisation. Images were produced for use in the planning enquiry to illustrates that design changes had been made. Other representations produced by the model formed the basis of the architects two-dimensional drawing set.

7.3 Moscow Tower

7.3.1 Background

Geometry for Moscow Tower (MOS) was proposed by architects RMJM. The construction method had not been considered in the conceptual design phases and a twisting forty five storey tower had been proposed. The tower had been modelled by RMJM and used to generate images that had won a competition. RMJM had employed facade consultants Newtecnic to develop a rational construction method. The author was engaged to develop a parametric model based on RMJM's conceptual idea and a facade construction proposal by Newtecnic. One of the primary goals of the parametric process was to produce models for communicating Newtecnic's rationalised construction method to facade subcontractors. This project illustrates a *rationalisation* procedure and a *design investigation* where representations were used to assess *construction logic*.

7.3.2 Overview of completed model

The geometric method of RMJM was to take a square floor plate and translate it vertically and rotate it by a fixed increment. This underlying geometric principle was parameterised and controlled with a few numeric variables. The theoretical surface that this generated was

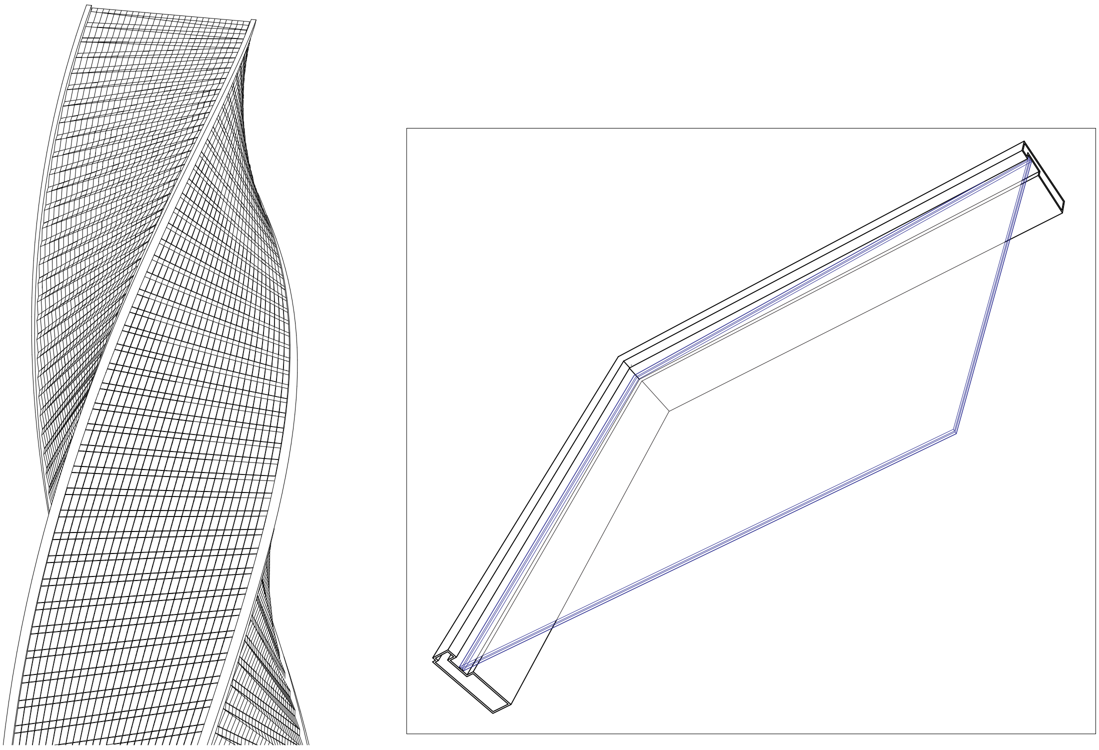


Figure 7.7: Proposed tower (left) and facade detail (right).

doubly curved (figure 7.7). Doubly curved panels were not an option and a flat panel solution was the goal.

Two *rationalisation* options were proposed by Newtecnic. The first involved dividing the facade at each floor level into two large triangles between floor and ceiling level (figure 7.8 top). A row of smaller glazed panels spanned between the ceiling and the floor above. This created facade units that were cranked. The second proposal involved a facade unit with deep section mullions and transoms which followed the tower twist (figure 7.8 bottom). Each frame had an extra wide glazing channel to take a planar piece of glass that sat at an angle in the channel (figure 7.7 right). In order to define the plane of the glass, both floor edges were effectively rotated in opposite directions about their mid points (figure 7.9). The angle they rotate was half the angle between two neighbouring floors. This procedure was applied for every glazed unit in the facade defining unique units for a single floor level but repeating for every floor.

The model was taken to Belefeld in Germany to a meeting with Schuco a manufacturer of facade units. The author sat with Schuco's design team and an architect from RMJM and adjusted parameters defining the configuration of the facade system. Manufacturing

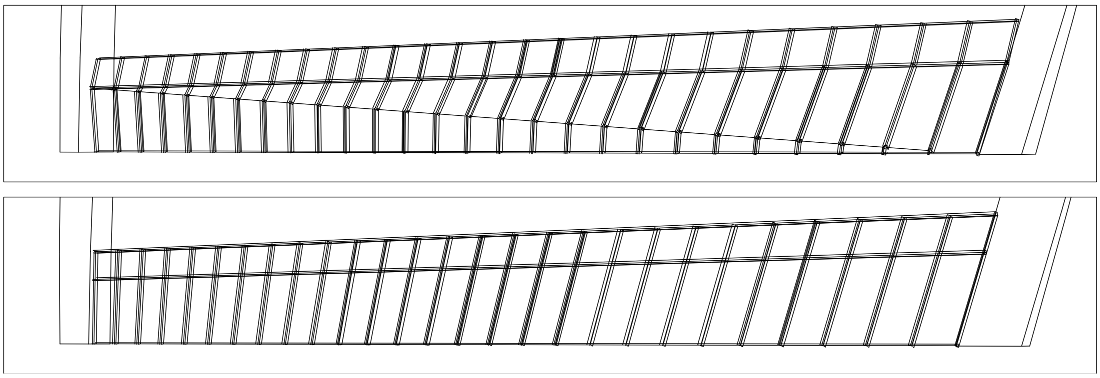


Figure 7.8: Proposed facade types.

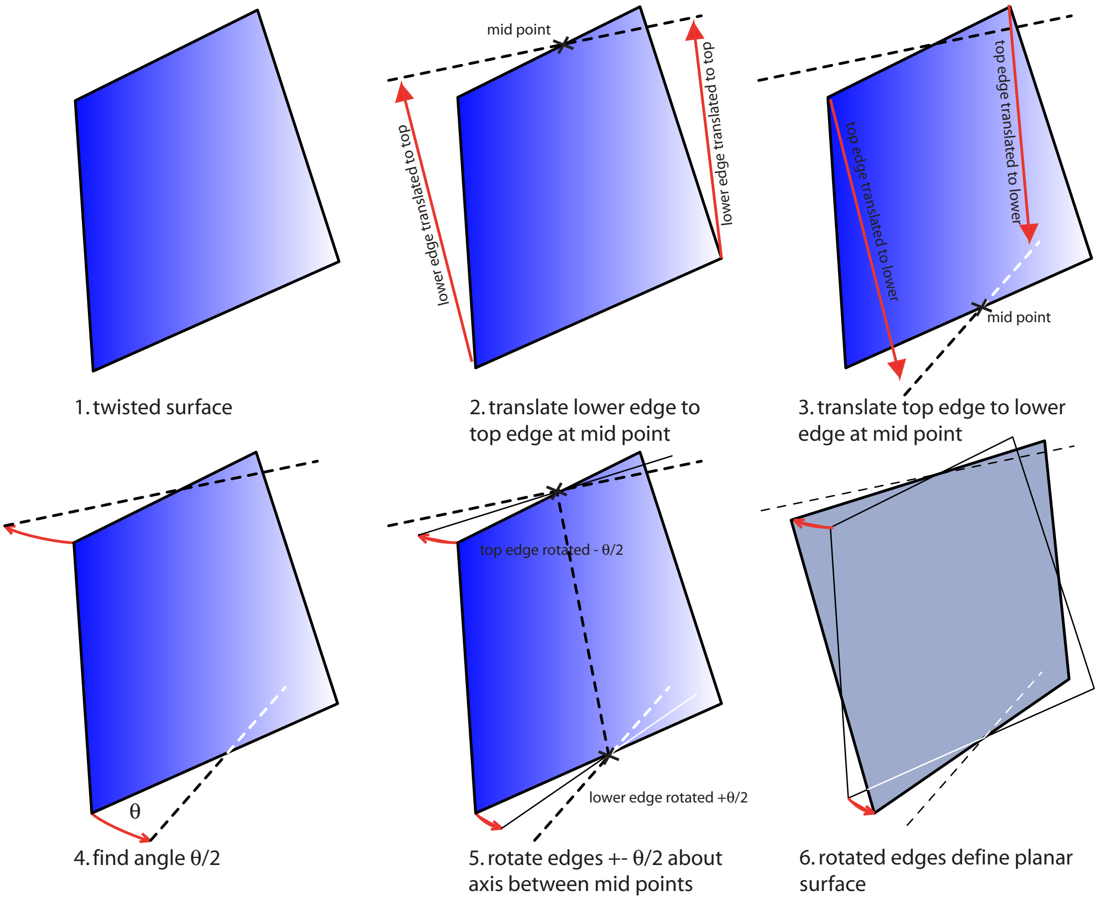


Figure 7.9: Defining planar panels.

constraints were discussed and incorporated into the model. The cranked system was rejected by the manufacturers on the basis that the joints were too complex. The design team then took the models of the twisted proposal and used them as the basis for their construction drawings for a mock up (figure 7.10).

Figure 7.10: Left and centre: facade unit mock up. Right: detail from parametric model.

7.3.3 Analysis

The process illustrates *translation* of a simple geometric procedure. MOS demonstrates generating alternatives as part of a narrow investigation where proposals were evaluated by specialists in terms of their construction logic. The parametric model was used to communicate design ideas to a manufacturer and demonstrate the possibility of construction. The case study illustrates a *rationalisation* procedure that implements a flat panel solution by taking advantage of tolerances in a framing system.

7.4 Gazprom Tower

7.4.1 Background

The design for Gazprom Tower (GAZ), proposed by architects RMJM consisted of a seventy five storey headquarters in St Petersburg for the Russian energy company Gazprom (figure 7.11). Parametric modelling was implemented during the design development stage, after a concept had been approved by the client. Facade design development had been subcontracted by RMJM to consultants Newtecnic. The author was engaged to support Newtecnic's design development process with parametric modelling. The parametric process was first concerned with the *translation* of geometric principles proposed by RMJM and *matching* the original design with a parametrically defined form. Newtecnic proposed a facade panelisation method, this too was captured parametrically and incorporated into the parametric model. The model produced geometry which formed the basis of drawings and visualisations which were used to assess the aesthetics of the tower. Analysis of the parametrically defined panelling system provided information for initial costing estimates.

Figure 7.11: Visualisation of Gazprom facades.

7.4.2 Overview of completed model

The geometry was defined with an adaptive floor plate. The method for a single floor can be considered as five squares arranged around a central point (figure 7.12 right). One edge of each of the squares is extended to the next square, the point of intersection defies a vertex of the floor edge. Repeating this for each of the squares defines a complete floor plate. The floor plate was translated upwards to define the next level. At each level the floor geometry was transformed, the squares rotate, scale about their local centres and the local centres translate radially from the floor centre point. This created a vertical set of individual floors which defined facades of twisted surfaces. Floor areas were recorded in spreadsheets and floor plans exported to individual model spaces within a single Microstation file.

The scaling, rotation and translation were controlled by graphically defined law curves (figure 7.12 centre). This graphical control allowed the parametric model to be closely matched to the original geometry by human interaction. Instructions from the architects would describe geometric changes in loose terms such as “can we make it a little bit fatter around floors forty-five to fifty-five”. The graphical control methods allowed an interactive soft approach for implementing these instructions.

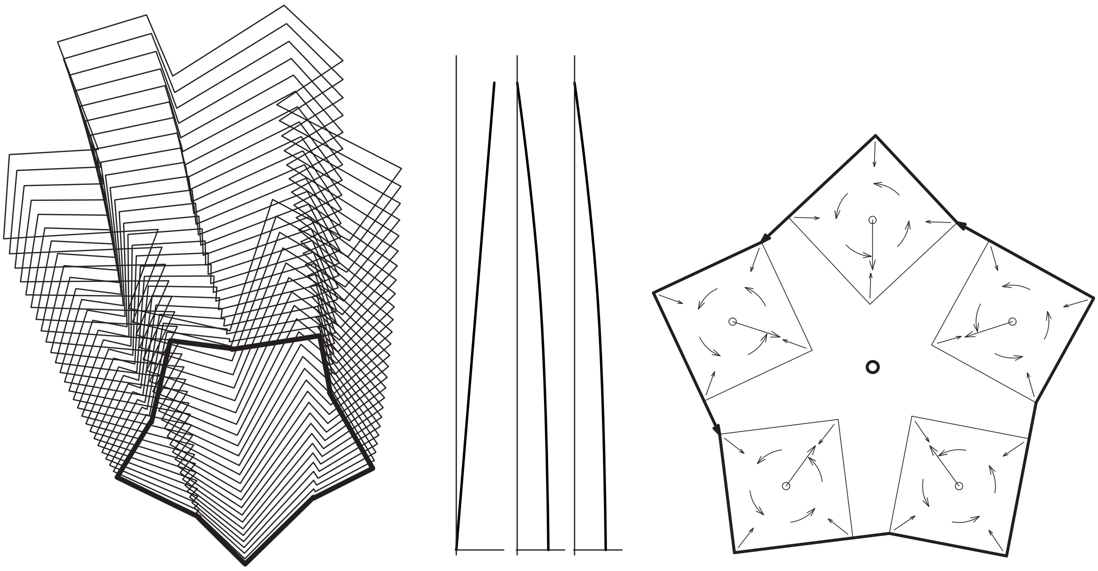


Figure 7.12: Gazprom tower. Left: floor plate variation. Centre: control curves for rotation, translation and scaling. Right: floor plate geometry.

The tesselation method proposed by Newtecnic was applied to the geometry defined by the floor plates in three-dimensions (figure 7.13 left) and in two-dimensions as unfolded elevations. The rotational symmetry of the tower defined five identical segments. Other than this rotational repetition, the twisting, scaling and translation of each floor level made each panel unique. Variation between some panels was very small and similar panels within tolerances could be identified. Panels were broken into two assembly types; a five sided unit and a four sided unit (figure 7.13 right top, heavy lines). Each contained a set of two or five triangular panels. Numeric data for each assembly type was extracted and compared to find panels which were identical within predefined manufacturing tolerances (figure 7.14). This identified groups of similar panels but many of these groups had few members. The cost of manufacture and construction of this number of non-repetitive elements was prohibitive for the design and subsequently the underlying geometry was altered to define more similar panel types.

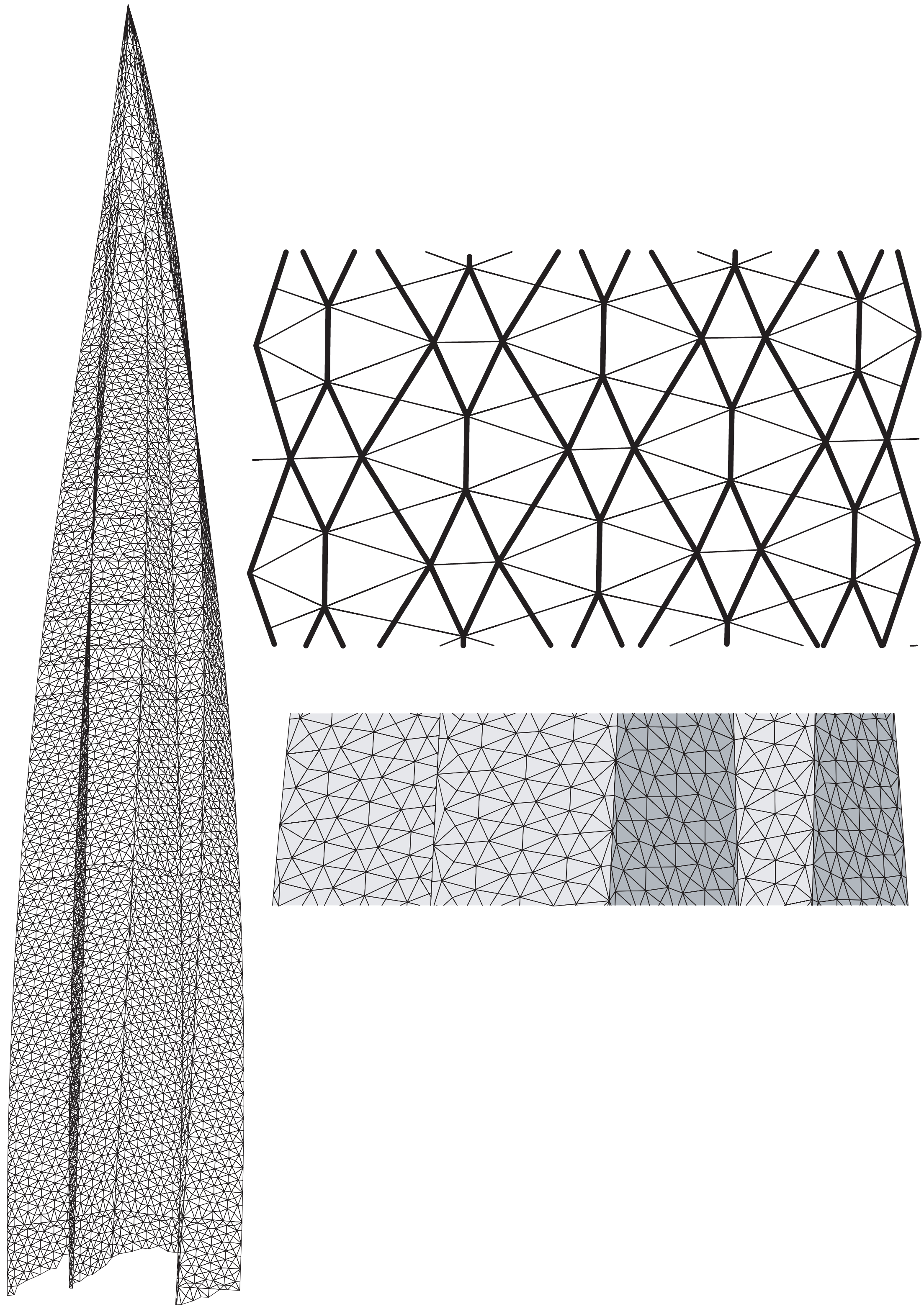


Figure 7.13: Gazprom geometry and panelisation. Left: full tesselation of Gazprom tower. Right top: assembly types (heavy lines) and panels. Right bottom: tesselation detail

NOTE: FIGURES REPRESENT ONE FIFTH OF BUILDING. ALL VALUES IN METRES SQ.

Assembly01			
TotalUnits	932		
CountTypes	176		
TotalArea	8895.77		
Types with 2 or less	106		
UniqueCode	**TypeCount**	**TypeArea**	**TotalAreaForType**
6.15	168	10.64	1787.12
6.075	136	10.63	1445.01
6.1	70	10.63	744.36
6.175	35	10.64	372.29
			0.00
7.1	14	10.63	148.80
4.35	13	9.04	117.47
5.325	13	1.16	15.11
7.175	12	10.35	124.25
7.225	11	10.25	112.71
4.425	10	9.04	90.35
6.2	10	10.63	106.30
5.3	9	10.63	95.67
5.725	9	7.45	67.09
7.025	9	10.63	95.66
7	9	10.63	95.66
8.075	8	12.22	97.77
5.825	8	9.67	77.34
5.25	8	10.63	85.01
5.475	8	4.39	35.12

Assembly02			
TotalUnits	476		
CountTypes	47		
TotalArea	1900.63		
Types with 2 or less	22		
UniqueCode	**TypeCount**	**TypeArea**	**TotalAreaForType**
4.7	226	4.25	961.59
4.725	33	4.26	140.67
6.7	30	4.26	127.66
6.375	23	1.89	43.58
			0.00
2.925	12	4.25	51.04
6.725	10	6.41	64.06
4.65	10	4.01	40.06
4.625	9	3.77	33.95
6.575	9	2.38	21.40
6.6	9	3.01	27.10
6.525	8	1.62	12.99
4.675	8	4.25	34.01
6.55	8	2.98	23.80
6.4	7	3.62	25.32
6.5	6	3.01	18.07
8.5	6	3.53	21.19
6.675	5	6.42	32.08
6.65	4	3.16	12.64
6.45	4	2.37	9.49

Figure 7.14: Grouping of panel types.

7.4.3 Analysis

The case study illustrates *translation* of geometric ideas in a process where the initial design idea already exists and the parametric task was to *capture design intent*, *match geometry* and *rationalise*. The design investigation was limited to studying a proposal for facade tesselation which was mapped onto an underlying geometric proposal. This involved defining detailed information on the number of panel types required for the proposed facade system and enabled *assessment of construction logic* and cost. Evaluation of this data later led to *rationalisation* of the underlying geometry to provide greater panel repetition.

Parameterising the proposed facade system provided the first opportunity in the design process to examine complete models of the facade. Prior to this the system had been considered too time intensive to model in a more traditional way. The parametric model provided the architects the opportunity to *assess the aesthetic* impact of the facade.

The case study indicated that graphical control methods could facilitate *translation* from verbal descriptions to geometric change. Requests from the architects for geometric change were expressed in loose descriptive language which could be interpreted by manipulating control curves until a satisfactory form was defined. GAZ is an illustration of a scenario where parametric modelling is undertaken by specialists external to the architectural design team. This corresponds with model described in chapter four, section 4.5 and illustrated in figure 4.25. This model offered the ability to work closely and share information directly with manufacturers. This was the case with this project. The model in chapter four, suggested separation between the architectural design team and the parametric modelling team could make translating design intent difficult. This proved to be the case with GAZ however the extent of these difficulties was lessened through the use of the graphical control mechanism.

7.5 Singapore Domes

7.5.1 Background

Singapore Domes (SING) case study consists of two domes (cool dry (CD) and cool moist (CM)) that enclose a cool dry and a cool moist ecosystem (figure 7.15). It is part of the Singapore Gardens in the Bay project (NationalParks, 2005). Construction began early in 2008 and completion is expected at the end of 2010. The domes are two similar designs, each is a composite structure consisting of a grid shell and a series of arches that are linked together by a series of tubular struts.

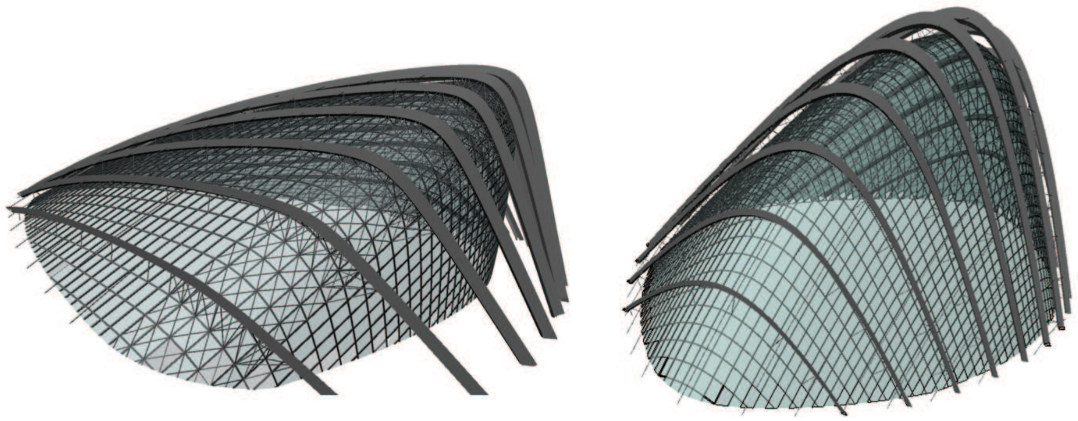


Figure 7.15: Singapore domes. Cool dry (left) and cool moist (right).

Architecturally the domes were designed by Wilkinson Eyre Architects (WEA), structural design was undertaken by Atelier One (A1). A1 employed Chris Williams (CW) and the author as independent consultants. Contractually A1 were responsible for structural design and communication of the geometry to the contractors. WEA had produced three-dimensional digital models as part of their design process. These models had been used for generating drawings and images of the domes. To improve the structural performance, geometrical changes were anticipated by A1. Manually remodelling geometry and redefining structural analysis files would have been too time consuming for the project time. A1 decided to pursue a parametric approach both for defining geometry and automating the set up of analysis files. The project contrasts other case studies in this thesis, as the parametric model was defined with code and not using proprietary software.

7.5.2 Overview of completed model

Both domes are defined using surfaces of rotation which are trimmed with a ground plane (figures 7.16 and 7.17). Two models for each dome existed; WEA's model and the parametric model. The parametric model was developed late in the design process. WEA's model had been used to develop detailed plans of each dome. The parametric model was used to develop the structural design. The parametric process was primarily driven by the need to match geometry defined by WEA.

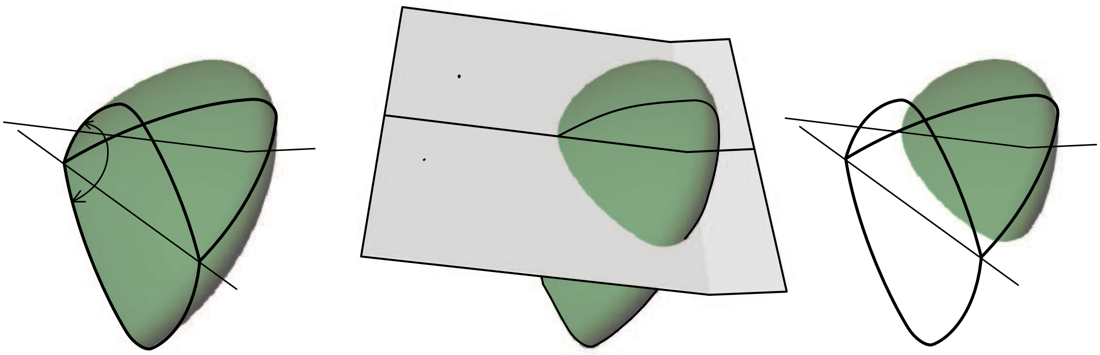


Figure 7.16: Cool dry dome; revolved surface, trim planes and trimmed surface.

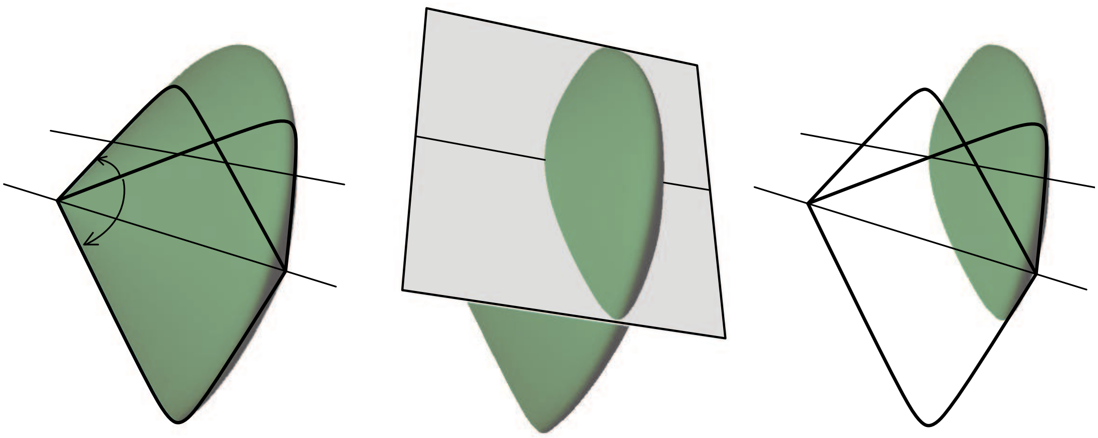


Figure 7.17: Cool moist dome; revolved surface, trim planes and trimmed surface.

WEA had used standard CAD tools and the parametric model recreated a similar set of procedures. WEA had used a curve constructed from tangential arcs with progressively decreasing radii for the CD. The CM used a hyperbola defined with a proprietary tool. These curves were then rotated around an axis and defined the longitudinal elements of the grid shell. Points spaced along these curves define the latitudinal grid members to complete the grid (figure 7.18).

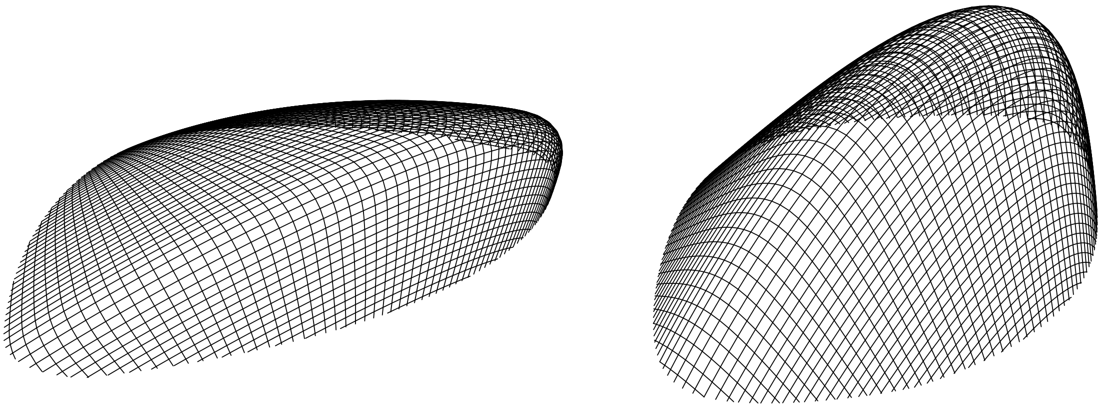


Figure 7.18: Grid shell elements. Cool dry (left), cool moist (right).

The parametric model was defined with C++ code. Analytic methods were developed for both of the domes. WEA's CM curve could be expressed analytically as a hyperbola (figure 7.19). WEA's CD curve from tangential arcs was redefined using a method similar to a hyperbola expect straight asymptotes are replaced with circles (figure 7.20). The analytical methods avoided the curvature discontinuity of tangential arcs and are not dependent on CAD transformation tools. Using an analytic method, a point can be defined on the rotated surface numerically. To define a point in WEA's geometric method required a geometric hierarchy; first the initial curve must be constructed points spaced along it and then copied and rotated.

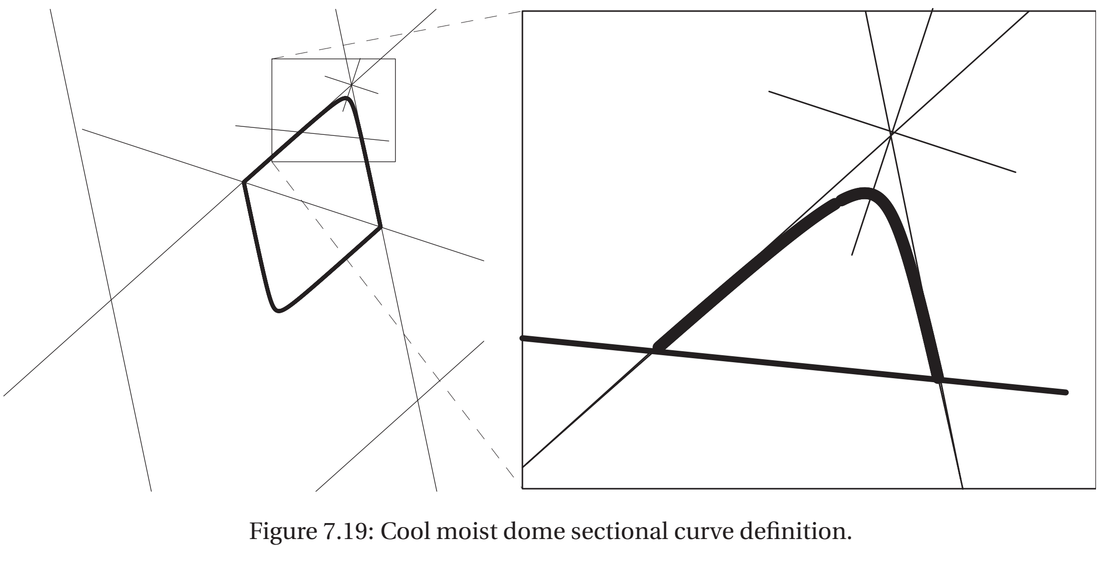


Figure 7.19: Cool moist dome sectional curve definition.

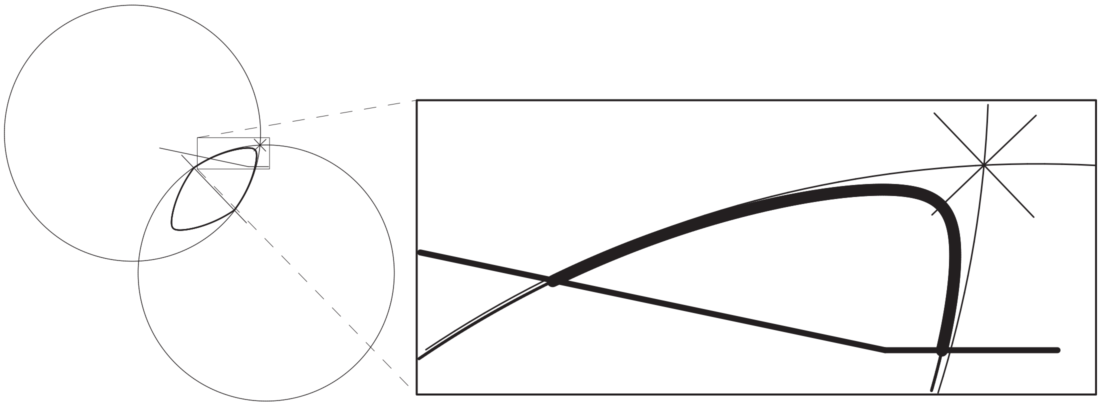


Figure 7.20: Cool dry dome sectional curve Definition.

The initial task was to try to find the parameter values for the parametric model which matched WEA's geometry. This process lasted several months. It was undertaken by overlaying the two models, both as two-dimensional prints, and as three-dimensional models on screen. Differences were noted and parameters were revised based on these observations. Despite efforts to give parametric control to the architects, changes could only be undertaken by one person. CW had defined the analytical methods and written the code. The ability to match geometry was based on his knowledge of the effect of changing parameters and the internal structure of the model. Throughout this matching period WEA continued to make changes to their model using their geometric method and the parametric model had to be adjusted to match. Foundations were constructed on site before the design was fully resolved and the parametric model was adjusted to ensure the structure would fit.

The parametric model generated multiple representations which were used to inform the design process. A range of geometric representations were created as CAD files, text files recorded the parameter values, glazing information and structural analysis data. Geometric representations included the complete theoretical surface from which each dome was cut, system lines or structural centre-lines, a three-dimensional model of the complete structure and glazing, all the arches in plan and outlines of all glazed panels in two-dimensions. Glazing information in the text files grouped panels according to the number of sides, specified the number of panels in each group and gave the total areas of glass. The text file containing the structural analysis data was formatted to be compatible with the analysis software Robot Millennium.

This structural data file was used by A1 to define their analysis model. In addition to the definition and control of the geometry CW and the author were engaged in verifying the structural design that A1 proposed. This involved taking A1's design and using an alternative structural analysis package called Relax (Williams, 2008) to analyse the proposed design. Worst-case loading conditions were selected and the deflections defined by the two analysis methods were compared. In order to achieve this, a simple piece of code was written by the author to automate the translation between the Robot data format and the format required for verification.

7.5.3 Analysis

The SING case study illustrates application of parametric design at a late stage in the design process. This occurred during the detail design stage, as a result the major tasks were *rationalisation* of the geometric method for one of the domes and *matching geometry* defined by WEA. The method implemented for defining the parametric model provides a counterpoint to other case studies in this thesis. The case study illustrates the benefits and difficulties of a purely programmatic approach to parametric design.

The rationalisation process involved developing a mathematically defined curve to replace a curve defined with tangential arcs. Parameterisation of this analytical method was implemented with a C++ program. This avoided the dependency on a sequence of geometric operations in a proprietary software. Executing the C++ program generated the geometry of both domes and the set of various representations. This included automating the generation of text files formatted for structural analysis and accurate definition of geometry for construction. This took only a few minutes, arguably much quicker than any parametric model created with proprietary software.

WEA were responsible for the geometry but the parameters defined within the code were an abstract mechanism that they were unable to control directly. In order to make geometric changes, WEA's intentions had to be translated from verbal descriptions or diagrams noting the discrepancies between the parametrically defined geometry and their intended geometry. These difficulties were compounded by the fact that two models existed for both domes and the long chain of communication.

Two models existed for both domes; WEA's intended geometry and the parametric model which defined structural geometry. This resulted from the late stage in the design that the geometry was parameterised. Architectural design of space planning had been developed to high levels of detail and it was too late to share a geometric definition. If the geometry had been parametrised earlier, a shared definition would have avoided the extensive effort spent *matching geometry*. Earlier parameterisation would have also presented an opportunity to conduct a *design investigation*.

The chain of communication began with WEA who were responsible for defining the geometry, A1 were committed develop a structural design based on this. CW and the author were employed by A1 to assist the structural design process by producing a parametric definition based on WEA's geometry. Instructions from WEA to make changes to parameters were passed to the parametric modellers via A1. It is suggested that this chain may have caused the *matching geometry* procedure to become protracted.

In conclusion, the case study suggests careful consideration of the point of parametric application and the position of the parametric definition in the work flow. Benefits of a code based model definition were observed in the speed of generating results, although the higher level of control abstraction should be considered. In this case, earlier application with the parametric model positioned as a shared resource between architects and engineers may have provided a more efficient process.

7.6 Training professionals

7.6.1 Overview

Projects reviewed in this section are the result of professional training sessions conducted by the author for Ian Simpson Architects (ISA) and Whitby Bird (WB) (now known as Rambol but referred to as WB herein). Each of the projects below illustrates at least one of the tasks, sub-tasks or procedures identified in the task structure.

The training sessions were held in the offices of both companies with small groups of five to ten employees. Both practices were working with Bentley's GC. Before the training sessions each participant supplied the author with information about a current project. This information either related to a particular issue with parametric modelling of the project or described a design problem for which the author was expected to propose a parametric approach. Projects from ISA are described first and were typified by an interest in modelling and geometry methods, automating the extraction of building data, establishing work flows and control systems. Participants from WB were structural and facade engineers and their focus was on rationalisation strategies.

The projects and models described below were developed over the course of a few days, compared to the months or years of other case studies reported in this thesis. The descriptions are short and are intended to briefly describe the project and identify the salient points. Each project is numbered and given the prefix ISA or WB to indicate the office it originates from.

7.6.2 ISA Projects

Fragmented model (ISA1)

The first ISA project was for an office tower that had already been modelled parametrically. ISA required model organisation suggestions to make it more logical and easier to control. ISA's model was unstructured and mixed steps involving geometric definition, extraction of representations and design investigation. The author proposed *fragmenting* the model into four logical chunks; control, form, floors and facade. Each fragment had a series of technical problems and parameters associated with it and they could be dealt with incrementally. The complete set of control parameters were defined within a spreadsheet. The next step focused on the form of the building. This was created by defining vertex points using sets of point coordinates extracted from the spreadsheet. The vertices were then linked horizontally and vertically to define wire-frame geometry (figure 7.21 left). The next chunk involved controlling and defining a set of planes at each floor level using values in the spreadsheet. The planes intersected the wire-frame and defined the vertices for each floor. These were connected to represent the floor edges (figure 7.21 centre). The floor edges then became an input to the last fragment of the model which created a facade grid. The model operator controlled panel width and select which facade to investigate (figure 7.21 right)

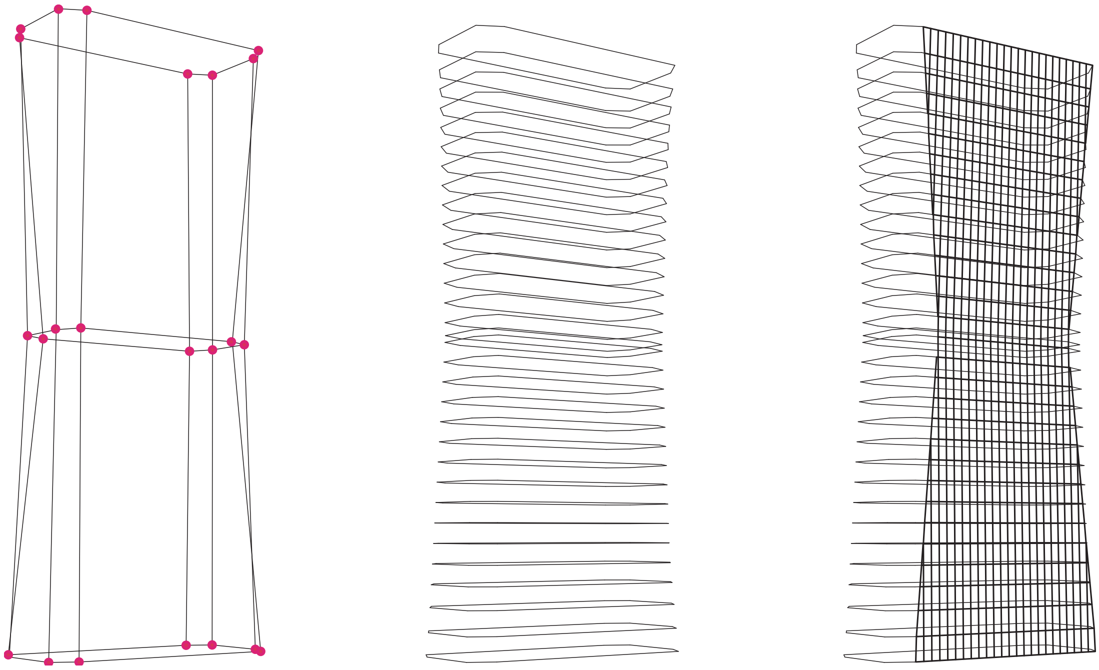


Figure 7.21: Fragmentation of model. Left: Vertices define edges of underlying geometry. Centre: floor edges. Right: facade grid.

Massing study (ISA2)

The second training project demonstrates the use of codification as an *amplifier* of design ideas to investigate a massing study. In this case the project had been developed using standard CAD and modelling techniques. The project architect was curious to see how it could be tackled parametrically. The design development process was focused on massing studies that were assessed visually (figure 7.22) and in terms of gross floor areas. An interactive control mechanism was developed to illustrate how the geometry of the proposed building type could be controlled, models and floor areas were exported. This was developed further to include a scripted loop that updated parameter values controlling building mass and automated the export of three-dimensional models and output of floor areas (figure 7.23).

Adaptive planar curves (ISA3)

The next project connects with other case studies in this thesis. This tower design method borrows the underlying geometric and control system directly from BLA, a project for ISA where the author was extensively involved. It is noted above that BLA is influenced by the

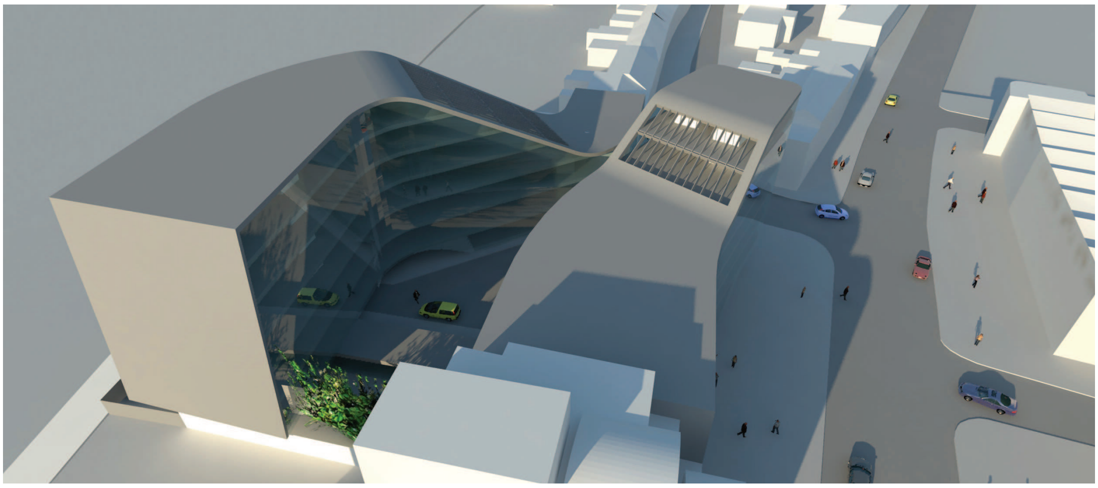


Figure 7.22: Massing study visualisation.

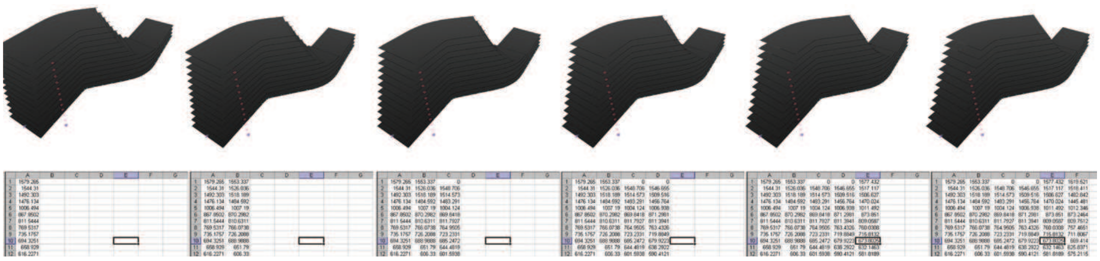


Figure 7.23: Automation of parameter change for massing study. Top: model geometry sequence. Bottom: updates to floor areas.

geometric and control systems of previous projects undertaken by the author. ISA3 was not just influenced by previous work, but actually redefines a previous model, demonstrating the procedure of *case retrieval*. The geometric method for ISA3 is illustrated in the bottom row of figure 7.24 which compares it to previous projects. The underlying principle for each of the case studies is a planar curve defined with simple rules. An array of the curves is created each represents a part of the building and each varies according to control curves. In the case of ISA3 the floor is defined in a way that constrains each edge to remain parallel at each floor level. This defines facades which are singly curved. A rational facade system consisting of four sided planar panels can be created. Control curves define the distance between the front and back of each floor plan and the dimension of the front edge varies with this distance (figure 7.24 bottom left).

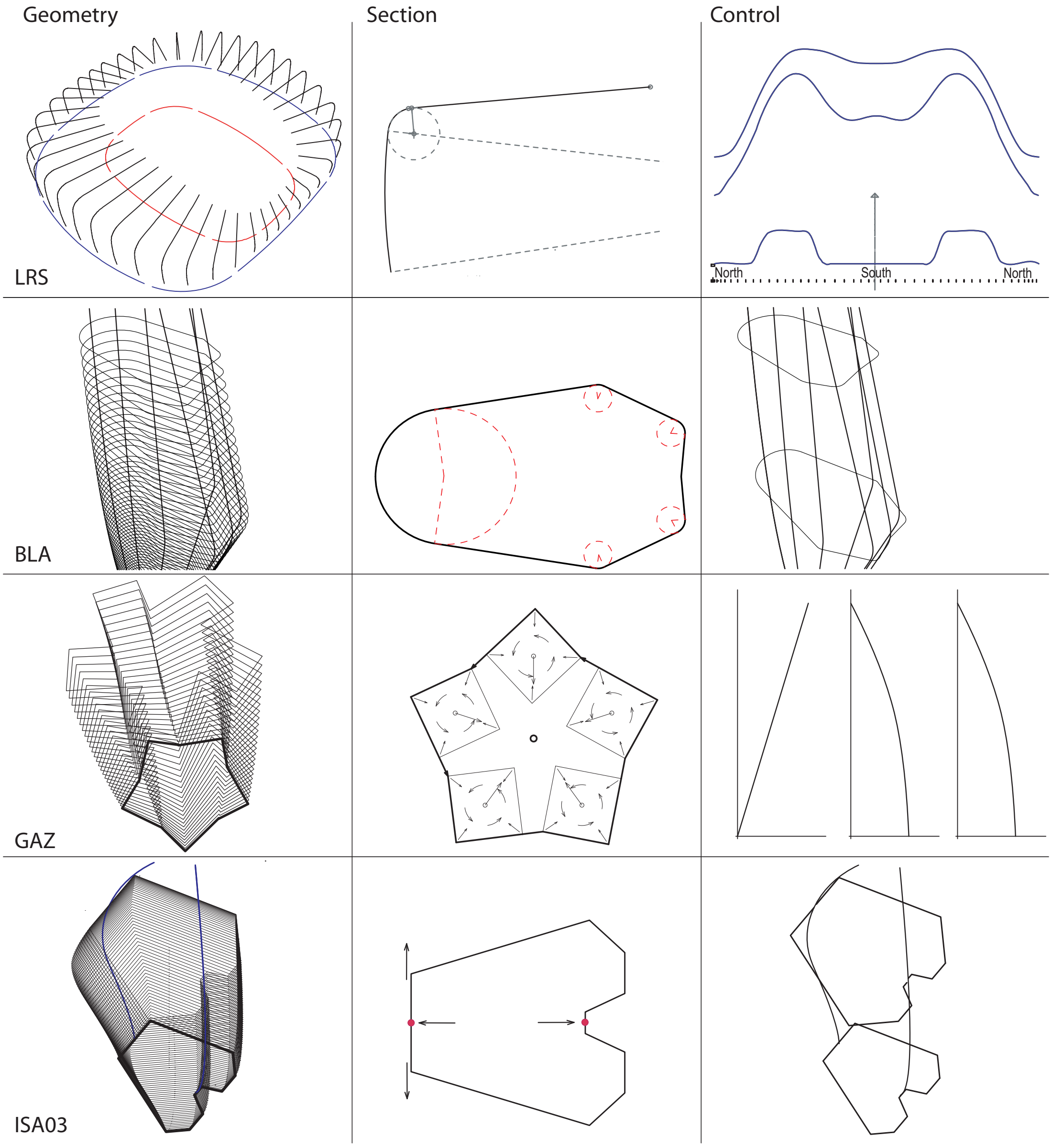


Figure 7.24: Development of the adaptive planar curve method. Top to bottom LRS, BLA, GAZ and ISA3.

Fragmented control (ISA4)

The final project developed for the ISA training session had already been through a design development process that had resulted in the definition of form as the result of massing studies. The concern for this project was how to develop a parametric model to investigate facade options using the existing models of the building mass. This illustrates a *control hierarchy* where building form is defined and controlled in a non-parametric CAD platform and imported into the parametric environment where the facade system is controlled parametrically (figure 7.25). Once the system is established, the CAD file can be edited and reloaded into the parametric model where the facade system can be applied to the new geometry. Working in this way requires the range of possible variations of the CAD model to be considered by the parametric designer and understood by the CAD modeller. ISA4 demonstrates this approach after the design development stage when significant changes to the underlying geometry are not anticipated.

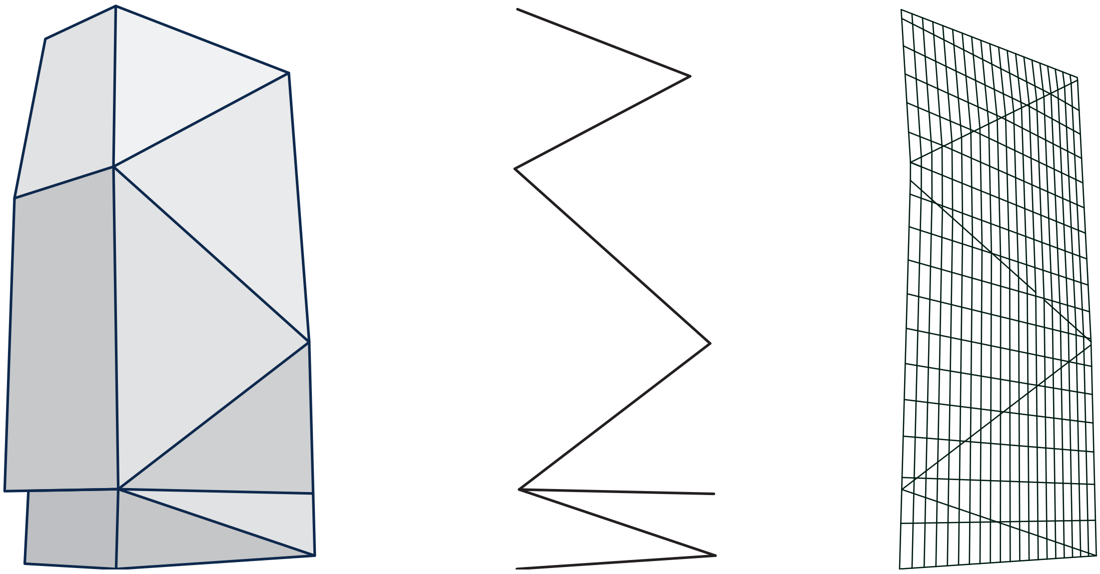


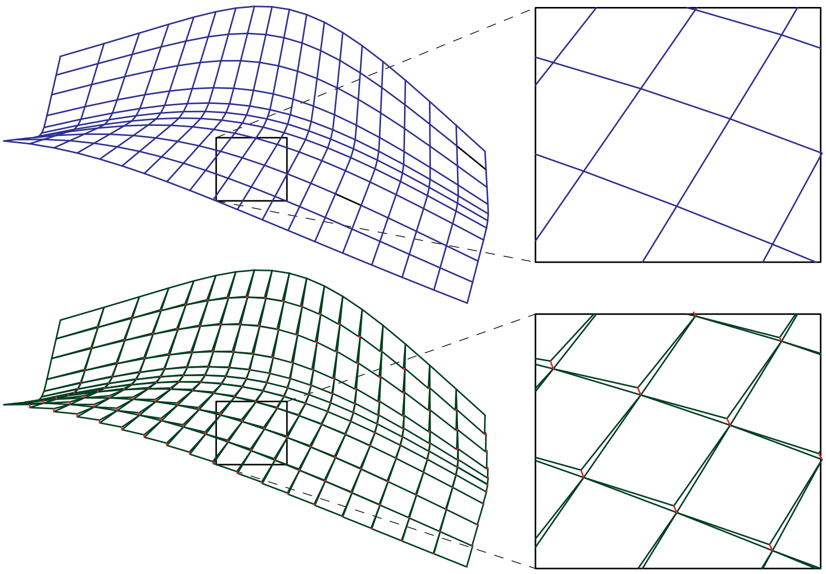
Figure 7.25: Model control hierarchy. Left: geometry by CAD modeller. Centre: facade edges extracted. Right: parametric facade grid.

7.6.3 WB Projects

The final ISA project has similarity with all but one of the WB projects. Generally the focus, for WB was on *rationalisation* of cladding systems to cover forms proposed by others. These projects all involved a *control hierarchy* whereby specific objects from CAD models were imported and formed the primary input to the parametric model. Which was then used to study rational panelisation. The projects described were developed to illustrate possible approaches and not complete solutions. It was anticipated that WB would take these proposals and use them in combination to efficiently develop rational cladding designs. The final WB project demonstrates the procedure *declare parameters rather than shape*, where the underlying control and output of a simple structural tower model is the focus of the modelling process.

Planar / twisted panel comparison (WB1)

The first WB project was an investigation into generating panels using a grid of points defined with the UV parameters of a surface. A model was constructed that defined a grid which was used to construct sets of either twisted or planar panels. For each method every panel had a value that described either its twist or deviation from the surface. To construct the twisted panels, four corresponding points in the grid were used to define the vertices, this was then repeated throughout the grid to determine a set of panels that covered the surface (figure 7.26 top). The model then wrote the out-of-plane dimension[1] of each of the twisted panels to a spreadsheet. For the planar panels the vertices were defined by taking three points, from a group of four corresponding points in the UV grid, and constructing a plane. The fourth point was then projected onto this plane (figure 7.26 bottom). The distance between the fourth point and the projected point was recorded in a spreadsheet. This system allows the grid definition to be varied and the designer can assess the opportunity for using planar panels within tolerances of the construction system as part of a *rationalisation* study.



out of plane

0.008	0.013	0.022
0.008	0.013	0.024
0.009	0.014	0.025
0.009	0.015	0.027
0.010	0.016	0.028
0.010	0.017	0.030
0.011	0.017	0.031
0.011	0.018	0.033
0.011	0.019	0.034
0.012	0.019	0.035

Distance - corner to surface

0.041	0.042	0.043
0.044	0.044	0.045
0.046	0.047	0.048
0.048	0.049	0.050
0.050	0.051	0.053
0.051	0.053	0.055
0.053	0.055	0.057
0.054	0.056	0.058
0.055	0.057	0.060
0.055	0.058	0.060

Figure 7.26: Comparison of panelling strategies. Top: twisted panels. Bottom: planar panels.

[1] In GC an out-of-plane dimension is the average dimension that each of the four vertices are from the average plane defined by four vertices (four points can define four different planes).

Projected grid to doubly curved surface (WB2)

The second WB project involved parametrising a doubly curve roof surface created by an architect to investigate the possibility of using four sided planar quads. Similar to the previous example this is a *rationalisation* procedure. A planar point grid is projected onto the surface (figure 7.27 bottom left). This defines a grid of points that is used to create panel outlines. The out of plane dimension for each panel was written onto each panel. The surface can be manipulated or the planar grid can be redefined and the effect of these changes is displayed on each panel.

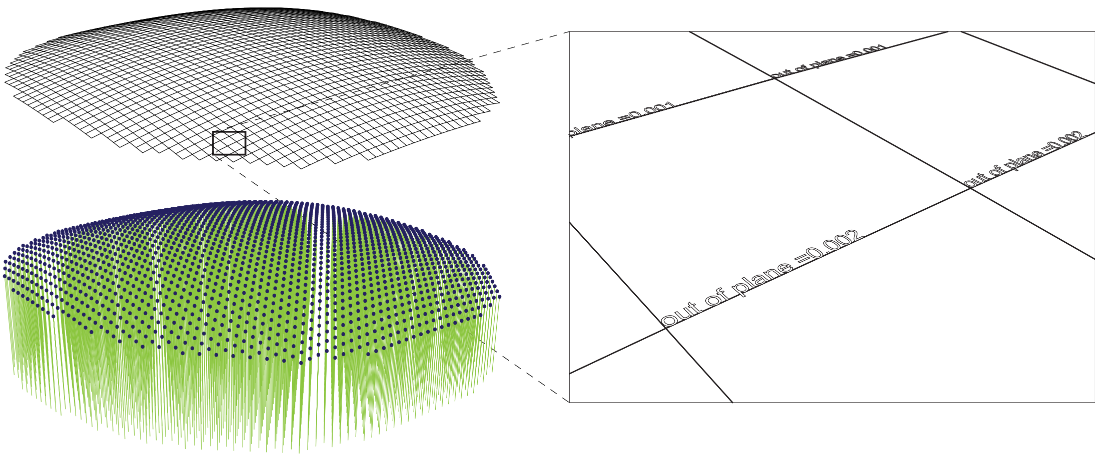


Figure 7.27: Roof panelling investigation. Bottom left: project planar grid to surface. Top left: panel outlines. Right: out-of-plane dimension written to panel.

Spherical patch (WB3)

The input geometry for the third model is a CAD file that defines a roof boundary and courtyard (figure 7.28). The architects of the roof required a radial cladding system. WB wished to investigate using a spherical patch to give *rationalised* planar cladding solution. The boundary and courtyard were extruded to create surfaces. These surfaces were intersected with parametrically controlled great circles, and arcs bounded by the extruded surfaces were extracted. The arcs were used to define a radial grid of planar panels. The parameters of the great circles could be manipulated to ensure the largest panels did not exceed construction constraints and that the curvature matched the original form proposed by the architects.

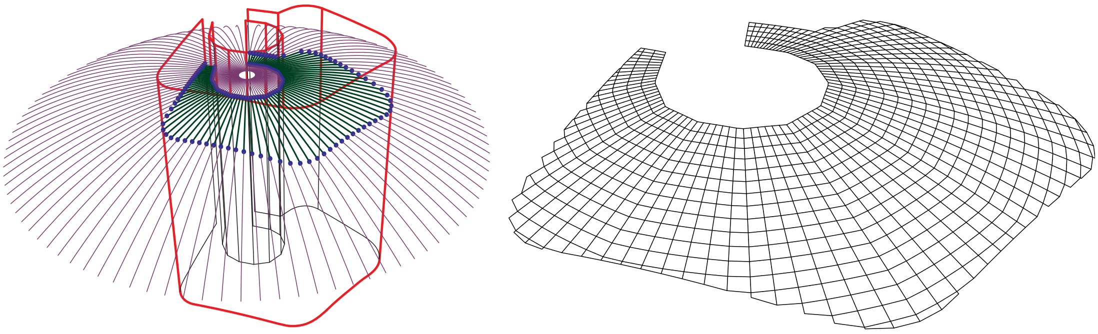


Figure 7.28: Spherical panelling. Left: imported roof outline is extruded and cuts great circles to extract radial arcs. Right: panel outlines.

Coloured panel analysis (WB4)

WB4 is the last project focused on investigation of a panelisation strategy. It is based on the import of geometry which requires *rationalisation* to determine a cladding solution. In this model, curves are imported and used to define a lofted surface. A point grid is defined using the UV surface parameters. Using this grid a scripted function creates panel outlines and the out-of-plane dimension of each outline is used to specify a panel colour. This method provides visual indication of areas of the surface where panel twist is greatest, which would inform how the grid is defined. An alternative for this system was developed where panels would be coloured if they exceeded a predefined out-of-plane maximum.

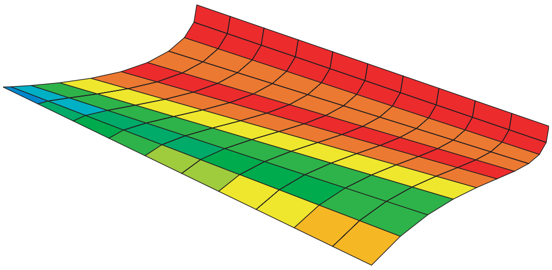
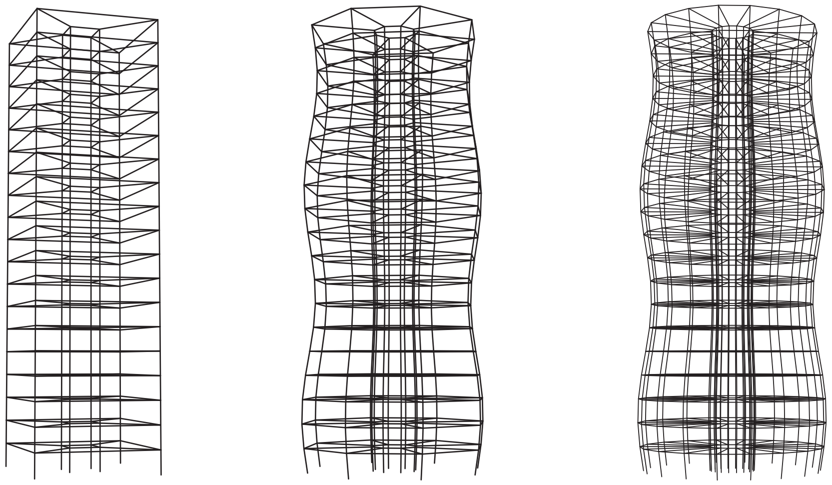


Figure 7.29: Panel colouring. Panels on doubly curved surface with function to represent out-of-plane dimension as panel colour.

Structural tower (WB5)

The final WB project illustrates *declaring parameters rather than shape*. Here, a structural system for radially organised towers was parameterised. Parameters and relationships were developed to control a tower radius, core radius, number of radial bays, number of floors and floor-to-floor dimensions. Functions could be specified to scale the radial dimensions (figure 7.30). The model automatically created a text file in a structural analysis format (figure 7.30 right). Nodes were numbered and recorded with xyz coordinates, members numbered and recorded with start and end node numbers and a member type. Later in the text file the properties of each type were defined. Developing a model in this way requires greater initial effort to declare the parameters, relationships and to set up the output routines. Once the model is set up the designer is then free to manipulate the geometry with the knowledge that the required output will be produced automatically.



node num	x	y	z
64	12.15	4	72
65	13.17	0	72
66	12.93	0.98	72
67	13.15	1.98	72
68	13.19	2.87	72
69	12.87	4	72
70	14	0	72
71	14	0.85	72
72	14	1.86	72
73	14	2.81	72
74	14	4	72
-1			

member num	start	end	type
0	6	5	1
1	6	1	2
2	6	0	3
3	7	6	1
4	7	2	2
5	7	1	3
6	8	7	1
7	8	3	2
8	8	2	3
9	9	8	1
10	9	4	2

Figure 7.30: Tower structure. Left to right: Geometry variations. Top right:node numbering and coordinates. Bottom right: member numbers start node end node and member type.

7.7 Teaching an introduction to parametric design

In addition to training sessions organised for professionals, the author has conducted several workshops in academic institutions (figure 1.1). These workshops were not part of the methodology described in the introduction, but were undertaken as part of the commitment the author made to the commercial sponsor. As this research progressed it became apparent that these could be used as an informal testing ground for the findings of the thesis. Observations on this opportunity are described in this section.

7.7.1 Parametric curriculum

The workshops were conducted with the sponsor's software GC. The first workshops were undertaken with GC's original developer Robert Aish. From these early few workshops a format was developed that involved software specific instruction combined with more general concepts of parametric design. These were introduced using some abstract modelling exercises developed by Axel Kilian and documented in GC's help files. In collaboration with Axel Kilian and Robert Aish the author developed a graphical summary of these more general concepts (figure 7.31). This has provided a valuable teaching resource and continues to be circulated amongst students of parametric design.

7.7.2 Strategy curriculum

Based on comments from participants the author observed that this carefully conceived course was too abstract for many designers. The main criticism was that it lacked instruction on how to apply the concept and techniques to practical problems. This confirmed the original motivation for this thesis, the need to overcome the complexities that parametric tools add to the design process and a need to develop practical strategies for implementation.

Subsequently the author developed an exercise for these short workshops that was grounded in the practical experience gained from the case studies in this thesis. Its aim was to demonstrate application of parametric design to a practical problem, but was deliberately presented to illustrate aspects of the task structure developed in the thesis (figure 7.33) and concepts in figure 7.31. This exercise was focused on developing a model for investigating the design of a tower, it is graphically summarised in figure 7.32.

The columns of figure 7.32 illustrate types of representation from left to right; control, floor plate geometry, panel geometry, panel layout and unfolded layout. The rows illustrate progressive steps in *design investigation*. The *multiple representations* indicate the procedure of *fragmenting* the model into chunks of smaller interrelated problems. Each column is a problem fragment; developing control methods, defining floor geometry, tiling the geometry, positioning each tile in two-dimensions and defining an unfolded pattern for model making.

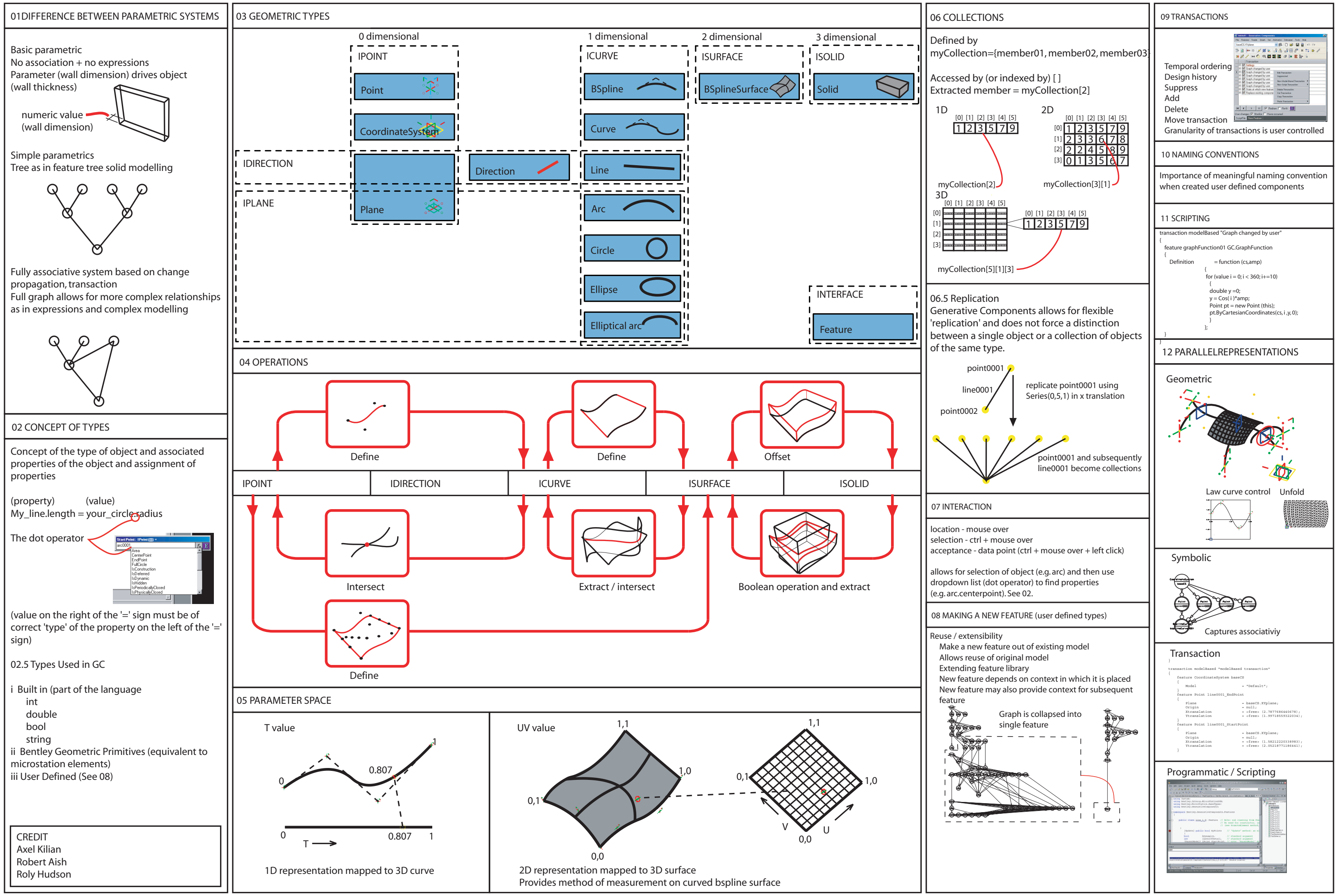


Figure 7.31: Parametric design course content.

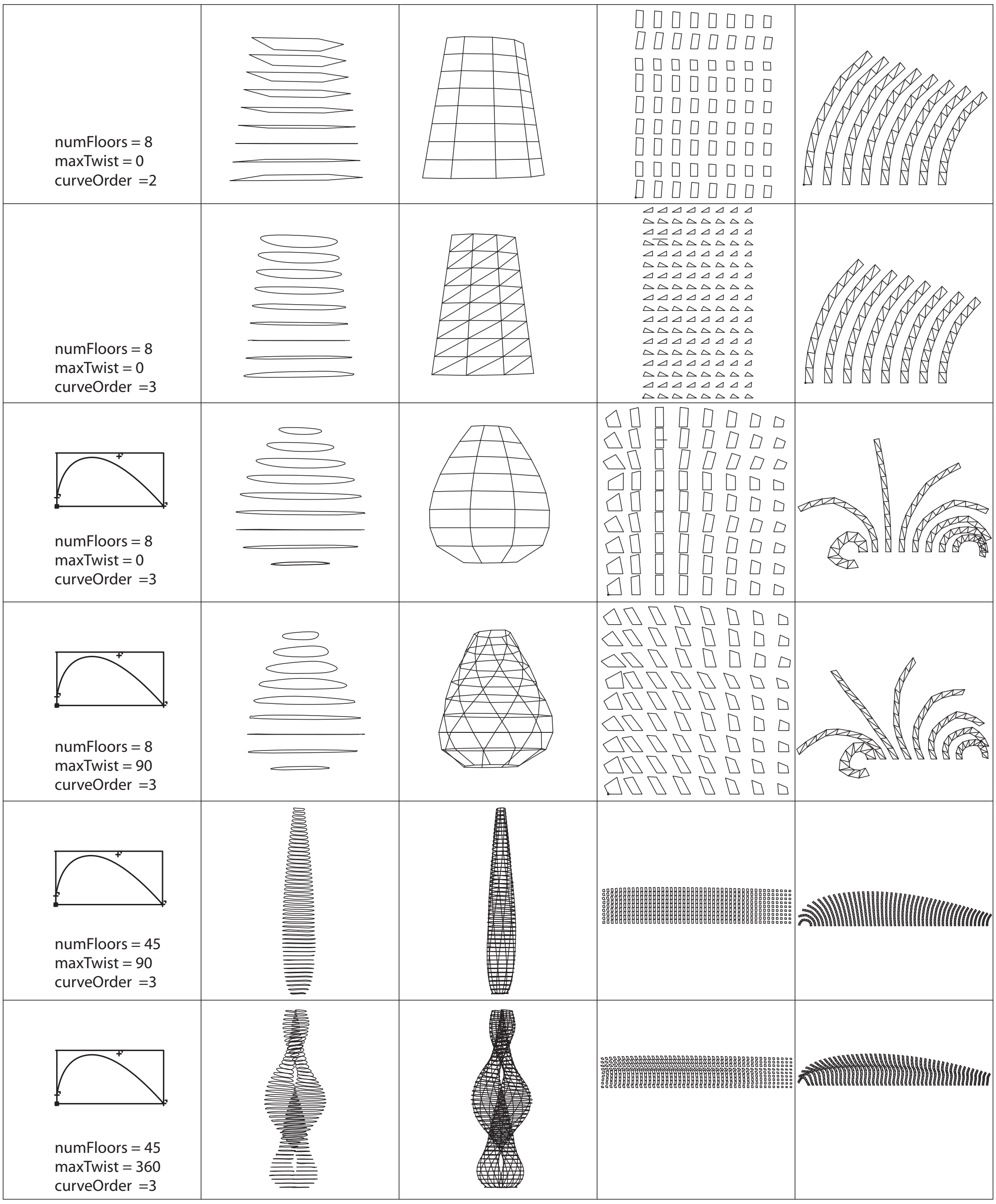


Figure 7.32: Parametric tower exercise.

The first row illustrates the first steps in the exercise focused on *declare parameters rather than shape* and the result is deliberately geometrically uninspiring. It shows establishing *control* methods and initiating simple *construction documentation*, in the panel layout and unfold representations, before considering form. The *control hierarchy* mixes numeric variables with dynamically controlled points defining a typical floor plate. The floor plate is transformed vertically, a control curve defines a non-linear scaling and a parameter specifying the total rotation of the final floor plate allows the tower to twist. The exercise deliberately illustrates the reasons for the initial effort in model construction. These become apparent when participants begin a *design investigation* by manipulating the model geometry and increasing numbers of floors while observing the representations update.

7.8 Summary

The contributions that these further case studies make to the parametric task structure are summarised in bold in figure 7.33. The further case studies have provided several supplementary examples to procedures in the task structure. *Use of library / memory* was illustrated by BLA and GAZ in their use of an adaptive planar curve method first used by the author on LRS. This recall of method from memory was observed to become a more formal process which was used as *case retrieval* for ISA3. ISA1 is an example of a clearly defined *fragmented model*.

MOS and GAZ demonstrate simple *translation* of ideas developed prior to parametric design. Following the translation to a parametric definition, this was then was used to *match geometry* defined earlier. SING involved an extensive matching process that suggested late application and control responsibility should be seriously considered. A *control hierarchy* may have helped to reduce the extent of the matching process for SING which involved *assigning initial values* for parameters that were later subtly adjusted. For ISA4 and BLA *control hierarchies* set up models where control was distributed, clearly understood and not dependent on an individual.

Automating the investigation of parameters was illustrated by ISA2 which *reduced the solution space using amplifiers* using script within the model. Assessing designs based on *construction logic* and cost was demonstrated by the panelling investigations for MOS and GAZ. The assessment for MOS went a stage further and the parametric model was used to communicate with manufacturers who produced a full scale prototype. The models for BLA and GAZ generated *aesthetic representations* that were assessed as part of the design development.

Creating a *structural representation* was one of the main reasons for parametrisation for SING. WB5 also generated a *structural representation*, this model was an example of

Task	Sub-task	Procedure	Practice example	Case study example
Create Model	Develop problem description	Assign function, structure, behaviour		LRS
		Identifiy parameters		LRS
		Fragment problem		LRS
		Propose-critique-modify		LRS
	Externalise ideas	Use library / memory		BLA GAZ
		Case retrieval		ISA3
		Declare parameters rather than shape		WB5
		Fragment model		LRS ISA1
		Multiple representations		LRS
		Propose-critique-modify		LRS MOS GAZ
	Capture design intent	Translation	03 11 13 16 22	LRS
		Propose-critique-modify		LRS
	Rationalisation	Post-rational	06 09 11	WB1 WB2 WB4
		Matching geometry	06 09 11 14	LRS SING GAZ
		Reduce geometry to simple elements	06 09 11 14	BLA MOS
		Flat panel	06 09 11 14 26	WB1 WB3
		Pre-rational	05 07 08 21	
	Control	Design surface	02 12 13 15 21 22 28	LRS
		Fragmentation / hiearchy of control	21 12	LRS BLA SING ISA4
Develop re-usable models	Develop problem description	Identifiy parameters		SBM
		Fragment problem		SBM
	Knowledge capture	Propose - critique - modifiy		SBM
	Externalise ideas	Declare parameters rather than shape		SBM
		Fragment problem		
		Multiple representations		SBM
		Re-structure model		SBM
				SBM
	Control	Fragmentation / hiearchy of control		SBM
	Implement in practice	Library / case retrieval		SBM
		Documentation		
		Training		
		Support		SBM
Design investigation	Find appropriate parameters and generate alternatives	Assign initial values		LRS SBM SING
		Reduce solution space using amplifiers		SBM ISA2
	Assess alternatives	Propose - critique - modify		LRS
	Generate and Test	Multiple representations to assess:		
		environmental analysis	11	
		structural	26 27	SING WB5
		construction logic	22	LRS MOS GAZ
		aesthetics		LRS BLA GAZ
Construction documentation	Share information	Geometry method statements	FP	
		BIM models and external manager	FG	
		Static model files	SOM	
		External parametric with direct links to sub-contractors	DTP	
		Share parametric defintion		LRS
		Cross contractural boundaries		LRS
		Check detail design		LRS
Split Opinions + critique	Point of parametric application			LRS SBM
	Depth versus breadth			SBM
	Use and development of libraries			SBM

Figure 7.33: Further case studies summary.

declaring parameters rather than shape to establish a model that would facilitate assessment regardless of the geometric definition. The remaining WB models provide a range of examples using different modes of representation to assess *rationalisation* proposals.

Chapter 8

Conclusions

8.1 Introduction

The aim of this thesis was to establish strategies for architectural parametric design. The strategies described in this chapter are informed by identifying general theoretical approaches and illustrating these with practical examples. This link between theory and practice has resulted in theoretically based, strategic frameworks developed to tackle practical parametric problems.

The objectives to achieve the thesis aims were identification of the **tasks** involved in parametric design and **considerations** that are taken into account when undertaking these tasks. Identifying **tasks and considerations** defines a comprehensive understanding of the choices available to the parametric designer. This generalised view of the role of the parametric designer is used to define strategies for approaching parametric design tasks in architecture.

The objectives were tackled by review of literature from theoretical and practical origins and through a series of case studies. The literature review established an outline parametric task structure and identified a series of areas that required further investigation. These areas were examined by undertaking case studies, which provided practical examples of tasks described in the literature, exploration of contradictory views and discovery of further tasks and considerations.

The tasks identified in the literature and case studies were mapped onto a diagram representing the task structure of the parametric designer, these were presented in the summary of each chapter. Figure 8.1 is a schematic view of the development of the task structure. There are five steps in the figure from left to right each representing one chapter of the thesis. Grey boxes indicate the contribution each chapter made to the parametric task structure. The area of the box is not proportional to the significance of the contribution. References made in this chapter to tasks, sub-task and procedures in the task structure are shown *italicised*.

Associated considerations were recorded in each chapter. Tasks were identified spanning the design and construction process. Each task was divided into a series of sub-tasks and these divided into sets of procedures. Each procedure is a documented means of addressing the sub-task. Practical examples corresponding to the procedures are also recorded in the diagram.

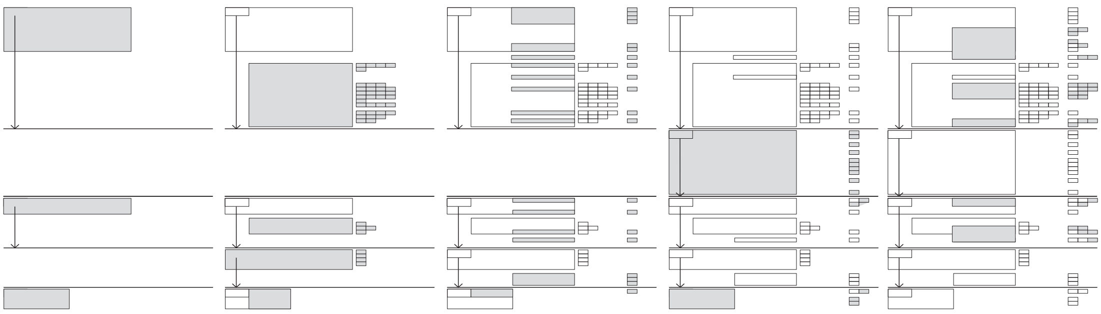


Figure 8.1: Task structure development diagram.

Figure 8.2 shows the final task structure, the corresponding practical examples and indicates how these relate to the proposed strategies. The diagram is not exhaustive and it is anticipated that it will be extended in the future.

First, this chapter summarises the development of the task structure. Analysis of the completed task structure leads to the proposal of five mutually dependant strategies. A combination of some or all of these strategies in response to the project context is anticipated, and this defines an implemented strategy. The formation of an implemented strategy is dynamic and is the result of continuous assessment of the project situation. This assessment defines the scope of parametric design throughout the design process and

Task	Sub-task	Procedure	Practice example	Case study example
Create Model	Develop problem description	Assign function, structure, behaviour		LRS
		Identifiy parameters		LRS
		Fragment problem		LRS
		Propose-critique-modify		LRS
	Externalise ideas	Use library / memory		BLA GAZ
		Case retrieval		ISA3
		Declare parameters rather than shape		WB5
		Fragment model		LRS ISA1
		Multiple representations		LRS
		Propose-critique-modify		LRS MOS GAZ
	Capture design intent	Translation	03 11 13 16 22	LRS
		Propose-critique-modify		LRS
	Rationalisation	Post-rational	06 09 11	WB1 WB2 WB4
		Matching geometry	06 09 11 14	LRS SING GAZ
		Reduce geometry to simple elements	06 09 11 14	BLA MOS
		Flat panel	06 09 11 14 26	WB1 WB3
		Pre-rational	05 07 08 21	
	Control	Design surface	02 12 13 15 21 22 28	LRS
		Fragmentation / hiearchy of control	21 12	LRS BLA SING ISA4
Develop re-usable models	Develop problem description	Identifiy parameters		SBM
		Fragment problem		SBM
	Knowledge capture	Propose - critique - modify		SBM
	Externalise ideas	Declare parameters rather than shape		SBM
		Fragment problem		
		Multiple representations		SBM
		Re-structure model		SBM
				SBM
	Control	Fragmentation / hiearchy of control		SBM
	Implement in practice	Library / case retrieval		SBM
		Documentation		
		Training		
		Support		SBM
Design investigation	Find appropriate parameters and generate alternatives	Assign initial values		LRS SBM SING
		Reduce solution space using amplifiers		SBM ISA2
	Assess alternatives	Propose - critique - modify		LRS
	Generate and Test	Multiple representations to assess: environmental analysis	11	
		structural	26 27	SING WB5
		construction logic	22	LRS MOS GAZ
		aesthetics		LRS BLA GAZ
Construction documentation	Share information	Geometry method statements	FP	
		BIM models and external manager	FG	
		Static model files	SOM	
		External parametric with direct links to sub-contractors	DTP	
		Share parametric defintion		LRS
		Cross contractural boundaries		LRS
		Check detail design		LRS
Split Opinions + critique	Point of parametric application			LRS SBM
	Depth versus breadth			SBM
	Use and development of libraries			SBM

Figure 8.2: Task structure.

determines which combination of strategies is selected. Factors affecting choice and scope of strategy are described. The core strategy and specific strategies for parametric design are then described in terms of the tasks, sub-tasks and procedures involved and these are related to practical examples. The contributions that the thesis has made to the field of parametric design is summarised and lastly directions for future work in this area are proposed.

8.2 Overview of task structure development

Figure 8.2 illustrates the parametric task structure developed throughout this thesis. It is colour coded to show where each task, sub-task and procedure was identified and where the corresponding examples were found. Contributions from the theoretical literature are in dotted, dashed blue boxes, practical literature in dotted green boxes and case study contributions in dashed red boxes.

The literature review first established a theoretic background for design, which formed a foundation for a set of theoretical views on parametric procedures. Broadly these defined two tasks *create model* and *explore design space*. These were broken into a series of sub-tasks and for each the theoretical literature proposed a set of procedures with the potential for tackling each sub-task. One contradictory view point to emerge from the theoretical literature was regarding the *point of parametric application* in a design process. Some argued for parameterisation after a problem description was known, while others claimed parametric models could assist in the development of problem descriptions. One of the arguments for later application is also a critique of parametric design. *Depth versus breadth* was a suggestion that parametric models could restrict the range of design exploration because of their requirement for a rigid hierarchical structure.

Practical literature confirmed the broad definition of parametric tasks provided by the theoretical literature. It did not provide practical examples of the sub-tasks and procedures proposed by theorists, instead the practical literature suggested further sub-tasks and procedures through descriptions of specific projects.

The first theoretical parametric task was *create model* by *developing a problem description.* Practical literature confirmed the *create model* task but suggests alternative sub-tasks.

Practical parametric design processes started once a design description existed. They were concerned with translating ideas developed by non-parametric designers into parametric models. This was undertaken by the sub-tasks of *translation, rationalisation* and *control.* Theoretical literature suggested that the *explore design space* task was a process of seeking a design from a very large range of possibilities. Practical literature described the *explore design space* task as making small changes to a design by generating and testing ideas based on performance or construction logic. The practical literature indicated that the parametric role also concerned the task of *contract documentation* and consideration of the method of sharing information. Practical literature presented views on the use of libraries of parametric models that contradicted theoretical opinion.

Analysis and comparison of the theoretical and practical literature identified that the case studies should seek to examine aspects proposed by theorists but not illustrated in practice and contradictory points of view. The case studies also sought further practical examples of sub-tasks and procedures that had been illustrated in practice. Seeking to observe these in a case study would be free of the constraints a practice has to consider when publishing its work.

Lansdowne Road Stadium (LRS) provided practical examples of sub-tasks and procedures that had been described in the theoretical literature as part of the *create model* task. In particular LRS illustrated how parametric design could be used to *develop problem descriptions.* This also contributed to the split opinion in theory of the *point of parametric application* as it demonstrated how a problem description could develop in the course of a parametric design process. LRS also illustrated some of the *exploration of design space* tasks. Exploration was started by *assigning initial values* extracted from a non-parametric model to a parametric definition.

The design of the LRS facade illustrated how the procedure *propose-critique-modify* could be applied as a design method. LRS extended the *construction documentation* task to include *sharing parametric definitions* and showed how the parametric designer may be required to *cross contractual boundaries* in order to help a project progress. LRS contributed a further procedure that involved performing parametric *checks on details* proposed by contractors.

The seating bowl modeller (SBM) identified the task *develop reusable models.* This shared similar initial sub-tasks and procedures with the *create model* task. The SBM extends these to include sub-tasks and tasks specifically related to developing systems for use by others and the need to accurately capture more extensive functionality. It identified the sub-task *knowledge capture* which was undertaken using a method of *propose-critique-modify*. The importance of *re-structuring models* was demonstrated during the development process of the SBM, and suggested that this procedure could benefit all model development tasks. The reusable model is for use by others in the practice so the SBM identified a further sub-task *implement in practice*. The procedures *documentation, training* and *longer term support* were found to be essential.

The SBM provided further practical examples of the *explore design space* task and the sub-task *find appropriate parameters and generate alternatives*. The procedure *assign initial values* was demonstrated by identifying parameter ranges from verbal descriptions given by experts. These ranges together with predefined sets of parameters illustrated how *reduce solution space with amplifiers* could be achieved in practice.

The SBM provided material which was used to examine the disputed claims identified in the literature. SBM suggests that the *point of parametric application* can proceed with incomplete descriptions of the problem. Rather than hinder development progress of the SBM, beginning parametric design with an incomplete problem description was necessary in order to identify parameters and refine models. The *depth versus breadth* critique suggested that while providing high levels of detail (depth), parametric models could restrict the breadth of exploration. SBM counters this claim by showing how a model structure can be developed that lets the user control the depth of detail. This enabled a broader range of solutions to be investigated while controlling model update times. Split opinions on the *use and development of libraries* was also addressed by the SBM. The case study defines a strategy for developing models for placing in libraries (reusable models). The SBM goes further and proposes that some models within libraries should be accompanied by a meta-library of parameter sets that form the starting point of new designs.

The summary of other case studies provided supporting examples for various tasks, sub-tasks and procedures. Tower projects illustrated how *use of memory* could be used to initiate model construction. The author's experience of previous projects was observed to form the basis for the geometric method used for each of the tower models. The tower design case study (ISA3) suggested that this previous experience could also formally define a generic method for tower design. This generic model was used as a starting point for a new model, illustrating the procedure *case retrieval*. The generic structural tower (WB6) system demonstrated a model focused on *defining parameters rather than shape*.

The further case studies provided additional examples of *rationalisation* and specifically *post-rationalisation* achieved through *matching geometry* by *reducing to simple elements* and seeking *flat panel* solutions. The implications of implementing a parametric model with a purely code based representation are illustrated by SING. In particular it provides a counter point to the *fragment and hierarchical control systems* observed in the BLA and ISA1 towers. ISA2 illustrated defining a scripted representation to automate design exploration and as such demonstrates the process *reduce solution space using amplifiers*. Use of *multiple representations* in the *explore design space* task was illustrated by SING and WB6, which automatically generated representations for setting up structural analysis. MOS and LRS demonstrated evaluation of full scale *construction logic* and the BLA model was used to generate and test alternatives based on *aesthetics*. SING's abstract mathematical *geometry method statement* contrasts the more procedural geometric method statements used by Foster and Partner's SMG, indicating the limits of this method of information sharing.

Observations of introductory training courses in parametric design conducted by the author support the original claims this thesis made. Designers experienced in modelling with non-parametric software find the concepts required for parametric design too abstract. These difficulties were one of the original motivations for undertaking this research. In the course of this research the author has developed a short training curriculum which includes some of the findings reported in this chapter. This involves participants tackling a practical building design task which reflects some of the strategic approaches described below. With careful and deliberate explanation this can illustrate the abstract concepts of parametric design and demonstrate the practical benefits of implementing these.

8.3 Analysis of task structure

Analysis of the complete task structure forms the basis for the proposed strategic approaches. The task structure indicates that the parametric process can be generalised as a series of mutually dependant phases and strategies are proposed for each. The need to gain an understanding of the problem defines the first phase, this is closely linked to a model construction phase. The model is then used to investigate options. Critique of the investigation will indicate changes required of the model or adjustments to the way that the problem has been understood. The final phase concerns sharing information for construction documentation and this too is closely linked to the model construction phase.

Two approaches for gaining an understanding of the problem are identified; knowledge development and knowledge capture. Knowledge development is required when a problem description needs to be defined. Knowledge capture is employed where the problem is already known and the aim is to parameterise it. This approach is common to the sub-tasks *capture design intent* and *develop reusable tools*. Emphasis in *capture design intent* is on matching existing geometry. Whereas for *develop reusable tools* the focus is instead making the captured knowledge usable and accessible to others.

The task structure indicates a series of common principles for constructing models. These principles form the core strategic approach. Model construction is directed by knowledge of the problem which has been either developed or captured. The sub-task here is to *externalise the ideas* defined by knowledge of the problem. This involves proposing a model structure, critiquing it and then modifying or restructuring both the knowledge of the problem and the model itself. Knowledge of the problem and the model construction are therefore interdependant.

Once a model has been defined it can be used to undertake design investigation. This will test the knowledge of the problem, the model construction and the designed artefact. In order to conduct the investigation the model must be controllable and produce results that satisfy the functional requirements defined by the problem. The results of this test can then feedback into the development and capture of the problem knowledge, the model construction and the design. The task structure indicates investigation procedures corresponding with early design investigations and later refining of details. Early design investigations are broader in the scope of options explored and relate more closely to the knowledge development approach. Refining details is a *design investigation* task that occurs with a later stage of design where the problem description is known or has been well developed.

The final strategic approach involves construction documentation. This too is closely linked to model construction, and determines the extent of the investigation stages. The task structure indicates that the representations required for contractors are the primary consideration. The extraction of these will need to be coordinated with the model construction. If extracting information for construction has been integrated into the design process, and tested in good time, design investigations can take place later into the design. Opportunities exist here for extending the role of the parametric designer. By sharing the model or the parametric skills it may be possible to add efficiency to the contractors workflow. Incorporating parametric design into the process of checking proposed detail design can reduce an otherwise manual workload. Gains in efficiency may also be achieved by the parametric designer crossing a contractual boundary to provide a service to a contractor while maintaining project continuity.

8.3.1 Strategic approaches

Analysis of the task structure and the associated considerations indicates five strategic approaches. The first is concerned with the sub-task of *develop problem description*, when the problem is known the second strategy provides an alternative which is focused on the sub-task of *capture design intent*. The next strategy has application across the design process. This core strategy concerns principles relating to the sub-task of *externalising ideas* which deals with the construction of models. This followed by a strategy that deals with the task *design investigation* and effectively tests the design, the model that produces it and the problem description underpinning it. The final strategy is oriented around the *construction documentation* task which is concerned with *sharing information*. The proposed strategies are referred to as:

kDev Knowledge development strategy

kCap Knowledge capture strategy

mCon Model construction strategy

dInv Design investigation strategy

cDoc Construction documentation strategy

The relationship of these proposed strategies and the task structure is illustrated in figure 8.3. Each of the specific strategies is dependant on the model construction strategy and it is anticipated that they will be used in combination. The next five sections describe each strategy in detail. Following this, the principles that determine how strategies are combined and implemented on specific projects are discussed.

8.4 [kDev] Knowledge development strategy

kDev should be implemented when a problem description is undefined or partially defined. It is highly dependent on both **mCon** and **dInv** (figure 8.4). The link between the three parts is essential, developing a problem description using a parametric process requires feedback from **dInv** as soon as a model has been developed, and a model cannot be developed until some problem description has been established. The feedback informs revisions to both problem description and the structure of the model.

The dependency on feedback from aspects of the **mCon** and **dInv** strategies means that **kDev** requires models to be established quickly so the iterative process of developing the model can begin. **kDev**, **mCon** and **dInv** need to be tackled simultaneously and constantly re-evaluated and revisited as the process progresses and design exploration is undertaken. The problem description develops through the process of defining models by externalising ideas and then assessing both the model function and its output. The following considerations are proposed for this strategic approach:

- Use when a problem description doesn't exist or is partial.
- Implement **mCon** and **dInv** simultaneously.
- Re-evaluate the problem description after assessing **mCon** and **dInv**.
- Identify parameters, functions and constraints.
- Make assumptions and test them.
- Fragment the problem.

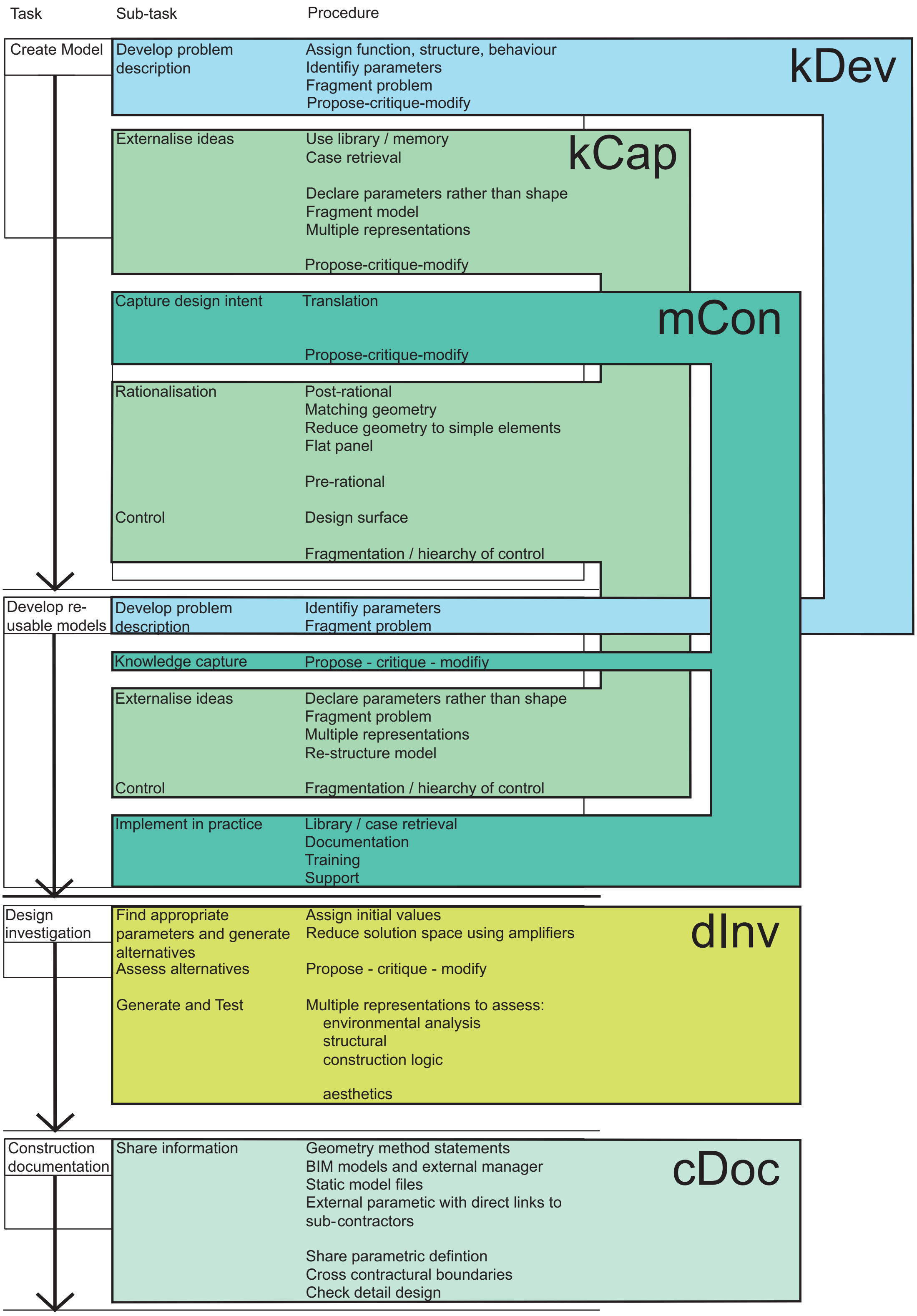


Figure 8.3: Relationship between strategies and task structure.

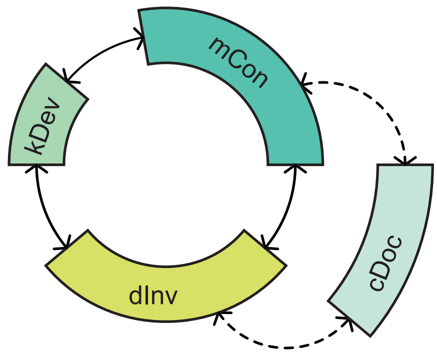


Figure 8.4: Relationship between kDev, mCon, dInv and cDoc.

This strategy challenges areas of theoretical thinking and the observed practical norm of parametric design where models are created once a problem description is fully defined. It suggests, in line with other theoretical views, that design problem descriptions can be developed through the process of parametric modelling rather than simply capturing predefined descriptions.

kDev is concerned with the sub-task *develop problem description*. In order to describe the problem it must be clearly understood. Initially this is about capturing what is known by simply *identifying and expressing parameters*. This requires some, but not a complete understanding of the problem in terms of parameters, functions to be delivered and constraints to be satisfied (Chandrasekaran, 1990). The result of this incompleteness can be seen in the simplistic early cladding models developed for LRS (section 5.3.1).

To develop an initial understanding of the problem one approach is to use a diagram to identify constraints and parameters mapping (Kilian, 2006b). However, this diagramming will require making informed assumptions of what is known to fill in the gaps in the problem description. The assumptions are then tested when the description is externalised as a model and used in **dInv**.

Assumptions made about the problem effectively apply a structure, which defines goals and the means of achieving them. This notion of applying a structure to a design problem was recognised in the design theory background as a typical way of approaching design problems. Descriptions of this structure in the design theory background were varied, it was seen in one extreme as originating from a rational understanding of the problem (Hillier *et al.*, 1972) and at the other end of the spectrum it was based on a visceral feeling about the problem (Darke, 1978). The **kDev** strategy is intended develop a problem description parametrically regardless of the origins of the structure imposed on it.

The origin of the imposed structure is not important, it provides an initial problem description that can then be further developed. It may be necessary to *fragment the problem* to break it into smaller, more manageable pieces that can be tackled semi-independently. The **mCon** strategy proposes fragmentation as a way of model composition, in a similar way the problem can be decomposed. If a problem is decomposed then at some point it must be re-composed. The order that the fragments are tackled and re-composed should be carefully considered as this has implications for the final model (Chandrasekaran, 1990). This type of fragmentation was observed in the cladding design task for LRS (section 5.3.1) where the problem was approached in a series of episodes. It started with simple problems like investigating patterns of tiling the surface which led into studies of specific component assemblies, the algorithms required to orientate those assemblies over the facade structure and lastly the configuration of parameters defining the position of assemblies.

Another way in which *fragment problem* can assist is to consider the problem in three areas; its intention or goals, the parts or components required, and what the parts or components need to do to achieve the goals. These are distinct areas of knowledge of the problem and can be described as function, structure and behaviour (Gero, 1990). The knowledge in any of these areas can be incomplete and as the design process proceeds further knowledge emerges. Using this system also offers a formal way of preparing to *externalise ideas* and actually construct a model. The components can be defined as geometric types and the behaviour of these defines the geometric relationships required to achieve the goals.

This type of approach can be seen in the early stages of the cladding design process for LRS (section 5.3.1) and in Hudson (2008c). Limited knowledge of function, structure and behaviour defined a starting point. The initial goal was identified as "cover underlying geometry", corner points and four sided polygons were the components and the behaviour was the way in which the points covered the structural centre-lines of the facade. This enabled the creation of a quick model which formed the basis of decisions which provided further knowledge and refined the problem description.

8.5 [kCap] Knowledge capture strategy

kCap is intended for situations where a problem description has already been developed. This strategy reflects the *capture design intent* approach observed in the published projects from practice and also corresponds to the task of *develop reusable tools*. It should be applied when the intention is to parameterise an existing design process and undertake an exploration with the goal of refining the existing design rather than redefining it. In a similar way to the **kDev** strategy **kCap** is dependent on **mCon** and **dInv** (figure 8.5). Feedback from the **mCon** and **dInv** is not used to redefine or substantially restructure the model or the definition problem description but to check that the existing design intent or design process has been correctly captured. Checking the knowledge captured is correct is particularly important if the model is to be used by several people. When implemented in practice, user feedback will indicate how well the existing knowledge has been understood and captured and the quality of the model and control mechanisms.

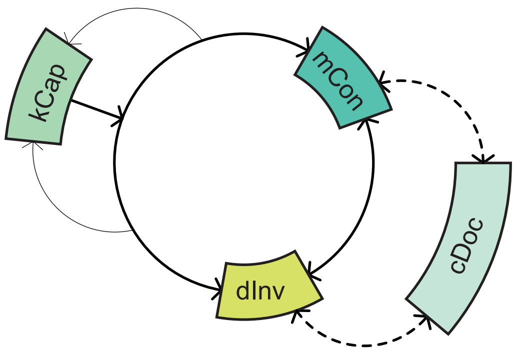


Figure 8.5: Relationship between kCap, mCon, dInv and cDoc.

Whether capturing an existing design idea or developing reusable tools with **kCap** the following considerations are proposed:

- Use when translating a non-parametric description to a parametric description.
- Anticipate differences in terminology.
- Construct initial models based on translation attempts.
- Assess proposed models to check design intent has translated.
- Rebuild or revise models.

- Anticipate cyclic development of model.

The *translation* sub-task involves converting from one language to another. The design is described in the language common to non-parametric designers, the design intent has to be extracted from this and changed into a form that describes the underlying rules and relationships so it can be parameterised. Changing from a non-parametric definition to a parametric model requires understanding of the design task. This has to come from material and descriptions provided by the non-parametric design stages and passed to the parametric designer. Projects described in the literature illustrate how this can involve sketches, traditional CAD files and models (digital and physical) and verbal descriptions (section 4.3.1).

The SBM case study illustrates how verbal descriptions based on extensive experience formed the basis of the knowledge capture (section 6.3.3). In this case *translation* was particularly challenging due to use of particular terminology relating to a very specific task and a tendency of expert designers to assume that the process they are familiar with is understood by those less experienced.

Regardless of the origin or type of information about the existing knowledge, the parametric designer has to make an attempt at developing a parametric model (by referring to the **mCon** strategy). Once some relationships have been established these can be externalised as a model. This will allow the assumptions made about the existing model to be tested and the model improved. The *translation* will probably not be completely successful on the first attempt. Progress in capturing the design intent or knowledge is incremental and iterative. It is suggested that the *propose-critique-modify* methodology is applicable as a procedure here.

Use of *propose-critique-modify* is illustrated in the design translation phase of LRS (section 5.3.4) and in capturing expert knowledge for the SBM (section 6.3.3). *Propose-critique-modify* had been suggested as a method of designing artefacts (Chandrasekaran, 1990). The LRS and SBM case studies demonstrate that it is also applicable as method for **kCap**. Both case studies show the importance of initially treating models as disposable and quickly producing them. This enables them to be rapidly critiqued then discarded if not of use or refined and incorporated into the next model. In this is way it is possible to reach a point where the parameteric model successfully captures the design intent.

8.5.1 Existing designs

The purpose of applying parametric design to an existing design is to refine it by testing its performance and making changes to the geometry. These changes would be time consuming if the process was undertaken with manual drawing and modelling. Parametrising an existing design can also include routines to automate repetitive procedures including aspects of construction documentation and generation of alternative representations. One of the aims for SING case study was to generate a text file in a format that could be used for structural analysis. The results of this were then used to adjust parameters to improve its structural performance. In the examples in the practical literature existing designs were typically parameterised as part of a *rationalisation* process. When undertaking the **kCap** strategy the designer should consider the following points:

- The goal is to refine not redefine existing design.
- Develop knowledge of geometry to provide rational solutions.
- Implement control and representation that facilitates matching existing design.
- Automate extraction of representations for design assessment.

Rationalisation can be broken into two tasks, *post-rationalisation* and *pre-rationalisation*. *Post-rationalisation* is a top down-approach where the final geometry is defined and the parametric design task is to find rational geometry that gives a very close match. *Pre-rationalisation* is a bottom-up or generative method where the parts are defined and building geometry is a result of combining these.

Post-rationalisation occurs when construction constraints are considered after concept development and is often driven by the financial need to find solutions with *flat panels*. The task involves matching existing geometry with simpler geometry that gives more rational cheaper construction possibilities. The process of matching existing design was observed in the case studies. Identifying a geometrical system that gives flat panel solutions and parameterising it would form the first step of the **mCon** strategy when capturing an existing design.

Various types geometric methods exist that result in planar meshes. The typical approach used in projects in the literature was to *reduce geometry to simple elements* using arc based methods such as torus and spherical patches, sheared cones and translation surfaces (section 4.3.2). Parameterisation of these geometric systems allow adjustments in geometry so the concept geometry can be matched as closely as possible. The initial stages of LRS concerned manipulating the model to match drawings and model submitted as part of a planning application. Much effort for SING went into getting the parametric model to match the architect's model.

The implemented control system for post-rationalising a design should focus on allowing manual adjustments to the parameterised geometry to try and match the original. This may require developing a representation method where both the rational parametric proposal and the existing geometry can be viewed simultaneously. It may be possible to measure between the proposed and the existing in order to quantify how close the match is. Depending on time available and team skills it may be feasible to develop a goal seeking algorithm to automate trying to find a best fit. A satisfactory match may be quicker to find by manually manipulating parameters on screen.

Practical illustrations of *post-rationalisation* from the literature are *Elephant House* (11), *Greater London Authority* (9), *Sage* (6), *Al Hamra Tower* (26), *Peek and Cloppenburg* (14) (section 4.3.2). Projects that resulted from training undertaken for Whitby Bird were focused on developing generic approaches to investigating opportunities for post-rationalising designs with flat panels on doubly curved surfaces (WB2, WB3, WB4 and WB5 in section 7.6). Parameterisation of BLA involved substituting a simple sheared cone geometry for an inclined cylinder (section 7.6). This made defining curves on floor plates simple arcs rather than slices from a cylinder.

Pre-rational is where a known rational geometric method is chosen at the start of the project. For Foster and Partner's SMG the *pre-rational* approach may also define the means of communicating to contractors. This suggests a connection with the **cDoc** strategy and early consideration of the means for sharing information. This can simplify shifting into detail design, fabrication and construction but can heavily constrain the design. *Pre-rational* approaches are demonstrated by *Albion Wharf* (8), *Free University* (7), *St. Mary Axe* (5) and *Bishopsgate Tower* (21) (section 4.3.2).

8.5.2 Reusable tools

The origins of the recommendations made in this part of the **kCap** strategic description originate from observations made during the SBM case study. These strategic suggestions are not about developing software (although there may be some similarities) but using an existing parametric software package to capture a commonly used process and make it reusable. It is anticipated that there are many architectural design tasks that could be captured as reusable tools. It is likely that these candidates for capture as reusable tools will be tackled in the future as awareness of the benefits, popularity and availability of parametric software increase.

The parameterised knowledge for the SBM was translated from descriptions given by experts on a domain of which the author had no prior experience. The intended use was by several individuals within one practice. Although this dealt with a large scale project it is believed that the strategy can be scaled. It would be applicable to smaller scale projects where the original knowledge comes from fewer people or an individual. The strategy is also applicable where the library (for which the tool is destined) is used by fewer people or even an individual.

Capturing the knowledge required for a reusable model differs from capturing the knowledge of an existing design. The extent of the functionality and the accuracy required are much greater. The process is therefore likely to be longer, involving more people both in development and when the model is in use. Based on these differences and analysis of the observations of the SBM case study, the following points are proposed for consideration:

- Develop a logical common language for variable and object naming.
- Develop the model in a modular or fragmented way to simplify extension and changes.
- Establish who is going to use the tool and what their skill levels are.
- Develop default parameter sets.
- Establish who is responsible for maintaining the tool.
- Establish who is responsible for managing the tool within the practice.
- Allocate time for developing a user manual and documentation.

- Allocate time for training users.
- Allocate time for modification following training.
- Anticipate longer term (on-going) support.

Common language will enable easier communication during development stages which will provide a logical step to defining meaningful parameter names. Logical parameter names will assist further development of the tool and this will be made easier still if a fragmented or modular structure that corresponds with the process being captured can be established. Knowledge of skill levels of the users will define the expected level of user interaction. This will inform the development of the tool especially the structure of control mechanisms and means for data input. Clear definition of responsibilities for maintenance (making changes to the script), management (storage of current versions and default parameter sets) will enable more effective use in practice. Allowing time for developing a user manual and documentation is particularly important if the tool is expected to have many users with the practice and if intermittent use is anticipated. The user manual can also serve as instruction for novice users in training sessions, for which adequate time should be allowed. Initial training sessions will provide the greatest source of feedback. The model developers should therefore allow for modification following this phase. Not all issues with the model will surface during early implementation, other issues will surface during application to projects which also may reveal the need for further or alternative functionality. Longer term support and maintenance should therefore be anticipated.

If the reusable model forms part of a library, it may be worth considering that it be accompanied by a meta-library of parameter sets, especially if the model has many parameters. It should have a set of default parameters so the user does not have to specify a complete set of values in order to configure a model. The default set of parameters will also serve as a reset function to allow users to return to a configuration using valid values.

The meta-library for the SBM consists of parameter sets that define built existing stadiums and a series of generic stadiums (section 6.3.4). A seating bowl model with minimal detail requires sixty parameter values and depending on size of stadium, number of tiers and level of detail, many more will be required. A typical four tier stadium will need approximately four hundred parameter values. The parameter sets therefore provide a very quick way to defining a starting condition which is close to a new design. However, users should be encouraged to develop an understanding of the values to avoid scenarios where default parameters are used without reasonable consideration.

8.6 [mCon] Model construction strategy

mCon defines a series of core principles for constructing parametric models. It is mutually dependant on other strategies that precede and follow it as it is both informed by and informs how these develop. Given some knowledge or description of the problem it is possible to begin to construct a model and *externalise ideas*. This is about capturing expertise, experience and constraints (Kilian, 2006a). It involves using software to explicitly develop relationships between objects. If those relationships or objects do not exist then bespoke tools must be constructed (Aish & Woodbury, 2005). It is propsed that the strategy requires consideration of the following points:

- Get initial ideas from a library, memory or retrieve a previous case.
- Treat early models as disposable.
- Anticipate incremental development.
- Propose critique and modify successive models.
- Think first of parameters and secondly shape.
- Consider model composition.
- Fragment the model and reassess as the project progresses.
- Assess design team size and skill levels.
- Identify key parameters.
- Implement a control hierarchy.

Initial ideas for the model can be taken from a *library or memory* or by *case retrieval*. Publicly accessible formal libraries of parametric constructs are available (Woodbury, 2007), others have been described (Iordanova, 2007) and the development of more is anticipated. The type of starting point found in this kind of library is abstract and can be downloaded, interrogated and then adapted to suit the problem being tackled. Ideas stored in human memory are based on previous experience (heuristics) of a parametric modelling task. These can provide a initial idea to begin a modelling process. *Case retrieval* is the most formal means of starting a design and involves taking an existing model and adapting it to suit the new problem.

The geometric solver to the SBM provides a practical illustration of the use of a *library* (section 6.3.5). An abstract model called "Goal Seeker" was downloaded from the design patterns repository (Woodbury, 2007). It was then examined, adapted, extended and incorporated into the SBM. It was used to find a solution where the seating bowl was based on an elliptical curve defined with eight tangential arcs. It sought to define the arc parameters to give an equal structural bay around the whole stadium. Drawing on previous experience and using an idea from memory was observed in the BLA project (section 7.2.2). This method of defining and controlling tower geometry effectively became a standard model defined within the practice's library. ISA3 illustrates this and the principal of *case retrieval* (section 7.6.2). For ISA3 the method is implemented in an almost identical fashion with subtle changes to the shape of the floor plan (straight lines instead of curves) and an identical control mechanism.

Another example of the use of a *library or memory* is when the preceding strategy **kDev** or **kCap** requires post-rational or pre-rational geometry to give flat panel solutions. This would involve selecting a known geometric method that gives planar panels from previous experience or a text book. The practical literature illustrates the dependency on torus patches, sheared cones and translation surfaces for achieving this goal.

Regardless of the initial idea, early models should be treated as disposable and not precious. They should be quickly constructed and tested against the current understanding of the functions and constraints of the problem. Findings from tests can then inform what modifications should be made, either to the model, the problem description or both. Subsequent iterations can then build on more refined model foundations and propose disposable modules that deal with more detailed aspects of the design. This disposable approach is illustrated in the LRS cladding design phase and in particular the early study models of tiling pattern and panel geometry (section 5.3.1). This showed how the model developed from simple origins which eventually defined a solid basis onto which more detailed aspects of the task could be added. When trying to capture knowledge for the

SBM the modelling approach was disposable. Early models were quickly developed and tested often three or four times before they were satisfactory. This illustrates the role of *propose-critique-modify* in the **mCon** strategy. Its the anticipation of several cycles of this that requires models not to be treated as precious.

LRS also identified the role that the *propose-critique-modify* method played in the actual construction of models. This was suggested in the theoretical literature as a way of actually designing artefacts and its use had been assumed to be in the *exploration of design space*. The model development process can also be regarded as a design process and *propose-critique-modify* is equally applicable.

When developing models it is suggested that design focus should be concerned with *declaring parameters rather than shape* (Burry, 1999). This requires considering what the model should do rather than what it should look like. Focusing on generalising methods will prevent restricting possible exploration later. This is illustrated by the model for defining a tower structure (WB06). The focus here was on the process of exporting the geometric data in a format required for setting up structural analysis, rather than the formal qualities of the tower. The implications of focusing on shape rather than underlying parameters are illustrated by the SBM (section 6.3.9). Initial effort was focused on defining a very specific front of bowl curve and possible generalisations were over looked. This later resulted in extra work to implement shapes that would have been possible had general parameters been originally implemented.

Composition of models should be carefully considered. This involves breaking the building designed down into sub-systems and components (Aish, 2005). Essentially this is about *fragmenting the model*. The level of process fragmentation will be indicated by considering logical decomposition, size of design team involved and their skill levels. This will also indicate possibilities for combined parametric and non-parametric approaches. Fragmenting the process may be beneficial in terms of spreading the work load and minimising dependencies on individuals and on specific software platforms. Team size and relative skill levels may change over the course of the project, therefore model fragmentation will need continuous reassessment and corresponding changes made to the parametric strategy.

The model composition for LRS illustrates an approach to fragmentation where tasks were broken into logical chunks that could be tackled semi-autonomously and even by different disciplines or different people (figure 5.2). Each of these tasks was described as consisting of further sub-tasks.

Model composition is closely linked to *control hierarchy*. Defining a *control hierarchy* requires identification of key parameters and consideration of the model users. Often only a few parameters contribute significantly to the size of the search space (Chandrasekaran, 1990), these are referred to as key parameters. They can often be recognised by experts in the domain of the object being designed. Many parameters may be included in the model but few will have an effect beyond controlling detail. The key parameters can define the first level of the control hierarchy.

Similarly to the *fragment model* procedure, *control hierarchy* requires assessment of team skill levels of the design team and an understanding of who the model is to be used by. If they are to be used and managed by an individual, but developed and maintained by one person this would suggest incorporating aspects of **kCap** for reusable tools. Graphical methods of control can assist communication with other members of the design team. Key parameters can be controlled in a more interactive manner, which will either allow less skilled users to control the model or provide a means for communicating the implications of parameter changes to non-parametric team members. Including input from other software or alternative representations can add further levels of control. These can be used for organising more detailed parameters or allowing input from other members of the team covering a range of skills and software preferences.

The use of a design surface may provide a useful way to structure a control hierarchy. The surface may be defined by lower level components such as a control polygon, lofted curves or script based equation. By using offsets normal to the surface, further levels of detail can be defined. Incorporating an intuitive control mechanism for the design surface has been described as beneficial when matching other geometry (Glymph *et al.*, 2004). The GAZ case study illustrated how graphical control curves enabled non-specific verbal descriptions of geometric change to be incorporated into the model.

Control hierarchy is illustrated in both the SBM and LRS. Key parameters for SBM were located as graphical control objects within the model and those controlling higher levels of detail were stored in a spreadsheet (section 6.2). Key parameters for sectional variation for LRS were defined in a set of graphical control curves (section 5.2.1). Visually, if these curves appeared smooth they implied that the envelope geometry is smooth. This was valuable for assessing the aesthetic qualities of the model. These curves formed a component of the *control hierarchy* used for the envelope geometry of LRS (section 5.2.1). A CAD file determining the layout of the radial structural grid and parameters controlling higher levels of detail were organised in a spreadsheet. These were combined with the control curves to define the geometry.

Control hierarchies are a means by which non-parametric members of the design team can be involved in geometric control. For example the imported CAD file and the spreadsheet in LRS (section 5.2.1) can be defined by individuals who are not familiar with technical aspects of parametric design. Other representations can facilitate distributed control such as the panels specifced by environmental designers in the Great Canopy project (section 4.3.3). Panel types are specified by colouring in a grid which is a mapped roof plan. The coloured drawing is scanned and in-house software recognises colours and defines the panel types and positions within the model. Distributed control systems can avoid bottle neck problems that can occur if a model is dependant on an individual.

SING demonstrated an alternative to hierarchical control systems (section 7.5), rather than progressively defining parts of the geometry and creating dependencies as in parametric software. The programmatic parametric model requires all parameters to be defined then code is executed and a series of output files generated. This was efficient in terms of the time required to produce the files. The need to specify all the parameters within the code and then execute the model meant intuitive input was not possible as implications of parameter changes could not be immediately assessed on screen. Manipulation of this model was only possible by the model creator /programmer.

Working with *multiple representations* also fragments the model. Use of multiple representations is recommended by Simon (1996) and reiterated by Kilian (2006a). Switching between representations can lead to seeing problems from a new perspective. The use of non-geometrical representations can reduce the emphasis on shape and shift focus onto parameters. Multiple representations are also essential for sharing information and become crucial when developing parametric strategies that include construction documentation or require any specialist assessment of the design. Multiple representations provide a means of communication for working with people from non-design roles who are not familiar with architectural drawings or examining three-dimensional models on screen.

The LRS model used text based, numerical and geometrical representations for control (section 5.2.1). It produced further representations to communicate with other specialists. Bspline surfaces were generated to create a physical wind tunnel model, full scale physical mock-ups tested the construction process and extraction of construction documentation. Wire frame drawings and renderings were developed based on three-dimensional geometry taken from the model, these were used to communicate to the client body and at public presentations.

8.7 [dInv] Design investigation strategy

Exploration or investigation has been described as the primary task for the designer (Kilian, 2006a). Fundamentally this is about generating a design and testing it against the requirements defined by the problem description. **dInv** defines a series of strategic principles for investigating design alternatives. **dInv** is closely linked to the earlier strategic phases. It tests if the problem description is correct, if the model performs in the required way and if the design satisfies the problem requirements. **dInv** should be undertaken with the previous stages simultaneously or at least as soon as sufficient knowledge of the problem has been developed or captured to construct a model. Feedback from assessment is passed back to the model creation phase and adjustments made to the model. When undertaking **dInv** the following points should be considered:

- Expect extensive investigation if preceded by **kDev**.
- Expect refining of parameters if preceded by **kCap**.
- Assign initial parameter values.
- Evaluate the design.
- Implement amplifiers to aid exploration of parameters.
- Identify representations for assessment and incorporate with **mCon**.
- Following assessment return to **kDev** and **mCon** and update.

If the preceding strategic approach has been **kDev** the **dInv** strategy is initially about investigating a broader range of alternatives which help to develop the problem description. This may involve substantial changes to the problem description, re-structuring of the model or both. As the design process proceeds, the extent of these changes will reduce and the **dInv** strategy will focus on revising parameter values to refine the design. The **kCap** strategy reaches the **dInv** stage with the knowledge that alternatives have been excluded by the non-parametric design process. The **dInv** strategy then serves to refine parameter values, problem descriptions and the structure of parametric models rather than suggest substantial changes.

The first procedure for the **dInv** strategy is to *assign initial parameters* to the model. These configure the model and provide a starting point. The process continues by assigning and evaluating further parameters. Changing the values has the effect of generating alternative designs which can be assessed in accordance with the design requirements and constraints.

If **dInv** follows **kDev** a wide range of parameters will be valid. It may therefore be useful to *reduce the solution space using design amplifiers.* The amplifiers were proposed in the theoretical literature and describe ways of improving the efficiency of generating new designs. Several were proposed and this thesis has been able to observe the practical implementation of those concerned with storing and recalling previous designs or parameters sets and the use of code or script to automate simple search processes. The SBM proposed a working method that involves assigning initial parameters using previously defined and stored model configurations. The massing study ISA2 used a simple coded loop to automate changes to a particular parameter and store sets of floor areas and corresponding three-dimensional models for iteration.

If **dInv** follows a **kCap** strategy, initial values could be extracted from existing models or they may emerge from verbal descriptions. LRS illustrated how these could be extracted from static models, while the SBM showed how, in the development process, values emerge from conversations with experts. These conversations also revealed valid ranges for parameters.

Once initial parameters have been proposed the design is evaluated. In order to evaluate the design it is important that criteria required for evaluation can be extracted from the model. If this has not been considered earlier it may be difficult (Motta & Zdrahal, 1996). It is therefore important that the assessment goals form part of the problem description as functions or requirements. The **mCon** strategy needs to consider the means of extracting the correct representation from the model so the assessment can take place. If multiple criteria form the basis of assessment then multiple representations will be required for assessment. The actual representation used in assessment may be the result of an intermediate representation produced by the parametric model.

The review of practical literature identified a taxonomy of design representations used for assessment and the intermediate representations that the parametric model must define:

- Aesthetics and construction logic (physical models from flat sheet laser cutting, rapid prototype data)
- Aesthetics (visualisation from three-dimensional models for rendering)
- Structural performance (analysis based on structural centre lines, analysis data file definition)
- Environmental performance (analysis based on polygon meshes)
- Acoustic performance (analysis based on polygon meshes)
- Costing (panel layout and material quantities for pricing)

Assessing aesthetics with physical models is illustrated by LRS and MOS. Both required representations to construct full scale prototypes of proposed facade designs. LRS and BLA illustrate how the generation of multiple representations is also used for aesthetic assessment. The SING model generated representations to establish structural analysis models. These were refined and analysed by specialists, their data files were then converted into another mode of representation in order to perform a check on the original structural analysis.

Assessment of design may require specialists in building performance. If this is the case assessment of those groups will be necessary in order to incorporate their needs into the strategy. In particular, ensuring that the model generates the required representations and consideration of how results from assessment are fed back into the model. The level of technical skills within the specialist groups will determine how information can be shared and what types of representation are required. It may be possible to share a parametric model. Sharing the model will take full advantage of the effort made to construct the model and could benefit the whole construction team. This would enable specialists to propose and implement parameter changes following their evaluation. The shared model will avoid repetition in rebuilding of models which can lead to wasted time and errors.

The benefits of sharing a parametric model need to be carefully assessed. If a model is shared the definition and control of editing rights should be determined. The time required to establish such a process may not be practical. Sharing a static definition may be beneficial when working with external specialists as it will provide a logical break which can clearly define contractual responsibilities, allow for switches in software platforms and reduce dependency chains.

Following evaluation the parametric designer should be able to return to either the problem description (if **kDev**), model structure (**mCon**) or parameter values and make changes according to the results of the assessment. The ability to identify where modification is required is dependant on knowledge of the structure of the model and the potential effect of parameter changes. Following modification the evaluation process begins again. This sequence was described as *propose-critique-modify* (Chandrasekaran, 1990) in the theoretical literature. The LRS cladding task validated this theoretic proposal (section 5.3.2). Panel positions were proposed, the effect in terms of conflicting criteria (ventilation, wind blown rain and appearance) critiqued and parameters modified. Modification was only possible through detailed understanding of the parametric model and the effect of parameters. It is used to develop the object being designed, the model structure and the knowledge of the problem.

8.8 [cDoc] Construction documentation strategy

cDoc strategy is intended for use when geometry defined by the parametric model forms the basis of the work for other members of the construction team. *Sharing information* requires the parametric designer to consider the different types of information format (representation) that each of the construction team members require. The need to extract representations means **cDoc**, **mCon** and **dInv** are interdependent. Extraction of information needs to be considered during model construction and as part of the design investigation.

The ability to *share information* will also be determined by the legal contract between the parties involved, the position of the parametric designer within the construction team and the skills and working methods of the groups with whom the modeller is sharing information. Possible representation formats range from exported CAD models to numeric data in text formats, procedural descriptions and parametric models. Contracts may be set up to enable a specialist to *cross contractual boundaries*, allowing a continuation in parametric modelling which could benefit the design process, effectively sharing skills as well as information. *Sharing information* is a reciprocal process, contractors issue information to architects for approval. Parametric design can be applied to *check detail design* and the extent of the **cDoc** strategy continues until construction.

When implementing the **cDoc** strategy it is proposed that the following items are considered:

- Implement early in **mCon** to test the process.
- Identify required representations.
- Assess contractual team's skills and methodology.
- Anticipate skill transfer.
- Issue procedural descriptions for simple geometry.
- Share parametric models if skill levels permit.
- Check details parametrically.

Incorporating aspects of **cDoc** with **mCon** early in the project allows the process to be partially tested in **dInv**. Considering and implementing **cDoc** early will also allow design investigation to continue later into the project lifespan. Testing is initially partial because it is unlikely that the full specifications of the required data formats are known early in the project. **dInv** can be used to test the **cDoc** strategy because they are both dependent on extracting representations from the model and sharing them with others. A taxonomy of representation types was defined in section 8.7. The required representations for particular specialists may not form part of the geometry defined by the parametric model. The model will need to be adapted to produce the required formats. Structural engineers and environmental engineers are known earlier in the design process but contractors and sub-contractors may not be. Assumptions will have to be made regarding the data formats required by contractors. The process of developing full scale prototypes, and scaled physical models can provide a test for the construction documentation and sharing information with contractors. Later the model can be adapted to incorporate the required representations when they are specified.

When contractors are known, their expertise should be assessed and their working methodology examined. This will identify what information they require, what format it should be, opportunities for sharing parametric definitions and determine what information they will issue to the design team for approval prior to construction. This assessment will define boundaries between the design team and the contractor and could inform the legal contracts between them. If contractors are unknown (which may be the case if the project is at a pre-tender phase) it may be possible to assume a flexible boundary and define the possibilities of skill sharing to allow individuals to cross contractual boundaries to assist project progress (although contractually this may present some complexity). The situation with the contractors will need to be reassessed throughout the design process. Understanding the contractor's abilities, requirements and what they will produce will determine the extent of **cDoc**.

The simplest level of representation to extract from the parametric model for construction documentation is geometry in a CAD file. If three-dimensional information is required it may be possible to simply export the required geometry direct from the parametric model. Three-dimensional representations may then be incorporated into a building information master model. Sharing CAD files in this way can define boundaries between responsibilities of different parties in the construction team. If two-dimensional data is requested it may be beneficial to define a drawing extraction routine parametrically and export drawings automatically to individual files. Coordinates or other numerical data may be required to supplement the CAD files and these will need to be considered as part of the model construction and routines developed to write to text files or spreadsheets.

LRS involved a two-dimensional drawing extraction routine for extents to floor slabs and sections. These were extracted and saved to individual drawing files and incorporated into the architects traditional drawing set where further detail and annotation was added (section 5.2.1). BLA incorporated a routine that extracted floor slabs and the positions and depth of mullions. Each was placed in a new model space within a single Microstation drawing file (section 7.2.2).

CAD geometry can provide the required information for setting up structural analysis but this involves additional manual work. Writing a structural analysis file in a text format can reduce later work by defining structural properties of members and load cases. If this is required, the procedure would need to be combined with the method of geometric definition. The basic data format requires all nodes to be numbered and recorded with xyz coordinates, members numbered and the start-nodes and end-nodes of each defined. Structural properties are associated with member numbers and loading assigned to each node or member.

WB6 structural tower was used to demonstrate a simplified example of this to Whitby Bird's parametric modellers (section 7.6). SING implemented the definition of a text file that described structural data and geometry. Using Robot (Autodesk, 2009) Atelier 1 refined the structural model produced by the parametric model. The structure was then analysed under several load cases and member properties adjusted until satisfactory results were found. This final state was exported as a text file and returned to the parametric modellers. The data file from Robot had to be converted to another structural data format and a secondary analysis was undertaken using a different method to check the proposed design.

Practical literature described sharing procedural descriptions. Foster and Partner's SMG describe this as a Geometry Method Statement (GMS) (section 4.3.5). The principle of a GMS puts contractors in a position where they recreate the geometry and in doing so take responsibility for it. This also ensures the contractor understands the geometric principles. The success of this method of data sharing is illustrated in Foster and Partner's projects the GLA and St Mary Axe where arc-based systems define the geometry. For the Smithsonian a GMS was combined with a NURBS based geometry. This meant the contractors had to employ a geometry specialist to reconstruct the model from the GMS. For SING a GMS was developed that documented the full analytical equations used to define the structural geometry and the cladding system. It is thought that the complexity of this was the reason that contractors were issued three-dimensional CAD files. For the **cDoc** strategy it is suggested that a GMS is used when the geometry method is simple or when contractors have the technical ability to reconstruct a more complex method.

Sharing a parametric model between members of the construction team may be a possibility if the skill levels of both sides are sufficient and time is available for pre-planning. This can enable a dynamic situation where different members of the construction team are responsible for different parts of the model. Each builds directly onto parts of the model defined by others. This sets up a chain of dependency where each level of a model hierarchy is controlled by one member and further downstream geometry defined by others is dependant on previous levels. Updated parameters can be issued and uploaded into each of the member's models. The dependency chain causes the updated parameters to propagate through the model and update the entire system. The situation should mean that changes in geometry can take place later into the design and construction process. The time taken for updates to fully propagate through the entire system should not be underestimated as this can limit the theoretical dynamics of a shared model.

Sharing of parametric models requires substantial planning and the benefits of a shared model have to be considered against the effort required to establish the system. If sharing parametric models is part of the **cDoc** strategy then it should be considered early in the process as it has several implications for the **mCon**. The parties sharing the model need to agree object naming conventions and geometric procedures. These standards should be integrated into the model and not be changed unless universally agreed. Early agreement should also be made on the exact responsibilities of each party. Who defines what geometry and who has the rights to change which parameter should be clearly determined.

The LRS case study illustrated how sharing a parametric definition is a possibility for **cDoc** strategy (section 5.3.3). In this case the architects were responsible for geometric control of the building envelope. Their model defined the interface between cladding and structure, which the engineers used as their starting point for developing the structural geometry. In addition to the structural geometry the engineers model defined an analysis data file. This involved assigning member properties based on structural logic and establishing a series of load cases ready for analysis. Parameters defining the envelope geometry could be changed and issued to the engineers. The structural model would be updated and structural analysis files redefined in the same day.

Transferring the skills of the parametric designer *across contractual boundaries* can benefit the project without intensive pre-planning. Skill transfer involves a parametric designer from the design team working with contractors for a period. This can allow contractors who do not have the technical capacity to take advantage of the parametric model while avoiding the time needed to pre-define the parametric model sharing protocols. This can reduce the need to reconstruct models, ensure contractors get exactly the information they need in the required format and automate repetitive detailing processes. This maybe essential in situations where the technical capacity of the contractor does not meet expectations that were defined at an earlier stage of the project. Assumptions made early in the design process can determine inappropriate contractual boundaries. If this is the case the project may benefit by allowing the transfer of parametric skills and it may be necessary to develop the contract in a way that allows this flexibility.

During the construction documentation, LRS indicated benefits for the construction team to allow the parametric designer to *cross contractual boundaries* and assist contractors in their work (section 5.3.9). Based on the original parametric logic, models were extended to automate the process of defining ranges of dimensions that generic facade components such as fixing nodes needed to tolerate. Parametric models were also used to automate the definition of acoustic panels.

Sharing information is not a linear process and opportunities exist in applying parametric design to check the design details when they are issued by contractors. The information produced by contractors can be issued to the architects for checking and approval before construction or manufacture. Traditionally the contractors drawings are described as "shop drawings", the contemporary equivalent is a "shop model" which maybe supplemented with numeric data. There are opportunities here for parametric methods to assess these proposals.

The LRS parametric model was extended to include the dimensions of generic fixings between facade and floor slabs to check for clashes with the facade panels and floor slabs (section 5.2.5). Clashes between facade panels were also checked by measuring the gaps between them. In total there were around 800 locations where fixings were used and approximately 4500 gaps between facade panels. Parameterising the checking process removed chances of human error and saved time.

8.9 Principles for implementing strategies

In the context of this thesis, a strategy is not a repetition of a previous method but is a thoughtful response, informed by experience to a specific situation. An implemented strategy is dynamic, it develops as new knowledge emerges about the context in which it is applied. The proposed strategies are intended to serve as frameworks which are informed by the experience gained by the research described in this thesis. When applied to a specific scenario they are intended to be refined and adapted and reflect the particular circumstances of the context. This section provides instruction on how to apply these strategies.

8.9.1 Situation assessment

Assessment of the situation requires identification of which design stages are to be undertaken with parametric design and what is the position of the parametric designer in the project.

Knowing or predicting which design stages are involved will indicate which of the strategies or which combination may be applicable and define the extent of effort required in strategic planning. Figure 8.6 shows the relationship between the proposed strategies and work stages defined by the RIBA's "Outline Plan of Work" (2008). It should be noted that the "Outline Plan of Work" suggests a linear sequence, but the theoretical literature indicates that design is cyclic. At the outset of any architectural process it may not be possible to know the extent of the work stages that will be tackled. Continuous reassessment of the situation is required throughout the design process for successful strategic planning.

The first strategic choice relates to the level of concept development. How well the problem description has been developed will determine the point at which parametric design is applied. If the project is in the preparation stages or the concept has not been developed and has not reached any formal stage then **kDev** will be applicable. This suggests that parametric design can form a part of the project appraisal and development of the design brief. If a concept exists and has already been developed then **kCap** should be selected.

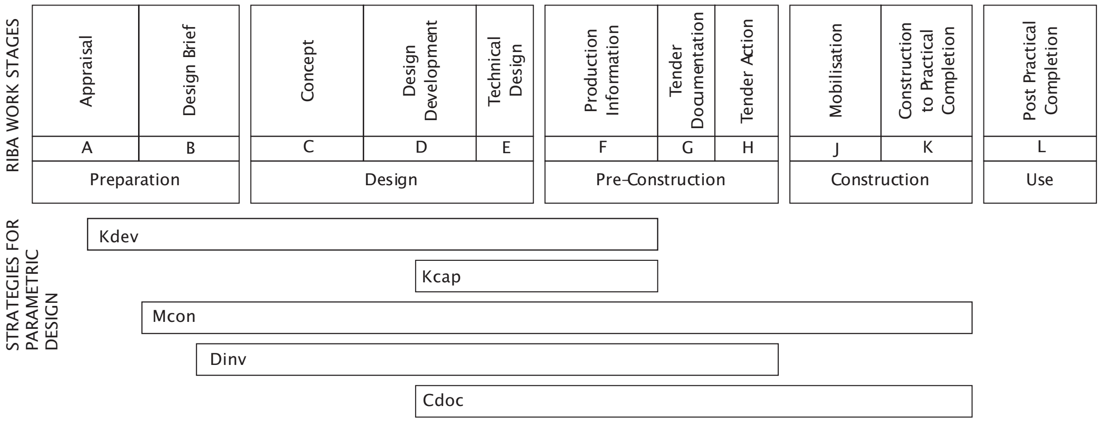


Figure 8.6: Relationship between RIBA work stages and strategies.

The **mCon** and **dInv** strategies should begin as soon as knowledge of the problem is established. The core strategy, **mCon** runs throughout the design process and it is informed by the strategy preceding it and those that follow it. The scope of the **dInv** and subsequent **cDoc** strategies will be determined by decisions made that define the extent of parametric design in the project. This may be difficult if the project is a speculative development, a competition or has not received planning consent. The extent of the **dInv** strategy is also dependant on the source of problem knowledge. A **kDev** strategy will require the **dInv** component to be more extensive and will investigate a broader range of options. If a **kCap** strategy has been employed, parametric design begins later in the design process and the **dInv** strategy will be shorter and less extensive as the non-parametric development will have defined a narrow range of design possibilities.

A short term view of the involvement of parametric design would suggest an approach where immediate problems are tackled quickly and without regard for issues relating to later stages. This may have the benefit of making design exploration freer and minimise wasted effort if the project does not reach later design stages. If the project does continue, the quick rudimentary approach will have indicated problems that will need to be addressed as the project reaches more detailed design and construction phases.

A longer term view suggests more extensive strategic planning and a combination of four of the strategies starting with either **kDev** or **kCap**. If this is the case then strategic planning will need to anticipate the potential involvement of other specialists and the sharing of information during the design development and construction documentation. As the design process progresses these considerations would need to be continually reassessed and the strategy redefined.

If the intention is to involve parametric design in the pre-construction or construction phases the **cDoc** strategy is applicable. Considerations made for this strategy should be instigated or overlapped with part of the previous strategy. **cDoc** has extensive implications for **mCon** as it defines the required model output representations. If **cDoc** is considered early in the process the **dInv** can continue beyond the end of the RIBA's proposed design phase (stage E).

The last aspect requiring assessment is the position of the parametric designer relative to the design team. Five different positions or workflows were described in section 4.2. Which of these reflects the current scenario will influence choice of possible strategy. **kDev** will not be possible if the parametric role is **External** and operates outside the architects office. An **Internal** workflow will find implementing this strategy problematic unless parametric designers are free to work closely with the design team. **InternalGMS** and **InternalBIM** enforce an information sharing method which may restrict the possibilities suggested by **cDoc**. **InternalARCH, InternalENG, Integrated** and **External** offer the potential of formally sharing parametric definitions.

8.10 Future work

The thesis has demonstrated the application of parametric design to developing various building designs, including those of unusual geometry and the capturing practical rule based systems. While novel geometry may be a passing trend, the thesis demonstrates useful practical methods. Benefits for other buildings and design process can be seen in both. As these benefits become apparent to a broader group of designers, interest in and popularity of parametric design is likely to increase. The increased availability of parametric software will reinforce the prediction of the growth in use.

The strategies proposed are based on review of literature and observations made from case studies. The suggestions are based on hindsight and further validation of the proposals is required. Attempting to formally apply the strategies on new design projects would test the proposals. This would establish the relative success or failure and indicate areas for and methods of improvement.

The strategies aim to provide direction for planning parametric design processes at a high level. The technical aspects of the tactics required for these strategies have not been discussed in detail in the thesis. These involve methods for developing parametric models that require technical skills in programming, scripting and dealing with specific software applications. Approaches to communicate these technical skills to people who have a background in design requires further investigation.

If the popularity of parametric design is considered in combination with current concerns for efficient buildings and technological advances, two broader future research directions are defined.

The **dInv** strategy suggests cyclic assessment and improvement of design proposals. The basis and methods of evaluation was beyond the scope of this thesis and only briefly discussed. Energy efficient design is currently a major concern. This could be combined with the **kDev** strategy proposed by this thesis. Using widely available environmental analysis software, conceptual design ideas could be parametrically developed and geometry tested and improved based on performance goals. Use of parametric modelling that incorporates or connects with performance analysis in early design stages could lead to the development of inherently efficient buildings. This could avoid situations where energy performance concerns are dealt with less effectively because they are considered later in the design process.

The **cDoc** strategy suggests close involvement for parametric design in the production stages of a project. It proposed that by combining **cDoc** early in the **mCon** strategy the process could be tested in order to maximise the benefits. Gains in efficiency in the construction process may be possible if parametric technology is combined with recent advances in manufacturing technology especially computer controlled production and assembly. In the design investigation strategy there is potential to thoroughly test proposed construction and manufacturing techniques in scaled models and on full scale prototypes. For the construction documentation strategy this technology has significant implications. Traditional processes of architects indicating design intent and contractors developing designs for construction may become obsolete. One possibility is that core parametric modelling skills are shared throughout the design team and used to combine specialist knowledge from all disciplines, from early design through to manufacture. The parametric designer's major concern would be defined as process engineering for design and construction.

8.11 Contribution summary

The primary aim of this thesis was to develop parametric design strategies. This was a response to an observation of the increasing popularity of parametric methods and that a new role was emerging to take responsibility for implementing the techniques in practice. However, it had been observed that parametric design methods involve abstract and complex concepts which can restrict the opportunity to take advantage of the benefits available. In the process of addressing the primary aim of the thesis the case studies undertaken have been objectively documented and contribute to the existing body of published material on practical parametric design.

This thesis has proposed five strategic approaches to applying parametric design in practice. These provide a framework for high level planning of practical parametric design process. They are intended for use in combination and this flexibility accommodates the uniqueness of architectural projects. They negotiate the complexities of parametric design by suggesting approaches that have a theoretical basis and are supported and extended by practical examples. They are:

kDev Knowledge development strategy

kCap Knowledge capture strategy

mCon Model construction strategy

dInv Design investigation strategy

cDoc Construction documentation strategy

The foundation of each strategy satisfies a further aim of the thesis, which was to link design theory and architectural practice in the field of parametric design. This was achieved by tackling the objectives of identifying parametric tasks and considerations. The result of this is a comprehensive understanding of the parametric design role. The diagrams that were developed in the course of the thesis illustrate the parametric task structure and identify links between practical examples and theoretical tasks. The literature review established a theoretical basis and identified the current state of practice. This provided a foundation for a parametric task structure. Comparison of these contrasting sources indicate trajectories that the case studies sought to examine further.

The proposed strategies emerged from analysis of the task structure and identification of common tasks, sub-tasks and procedures. The goal of the strategies is to enable a broader group of designers to take full advantage of the benefits offered by parametric design, implement more intelligent design processes that lead to better designs.

Glossary

Abbreviations used throughout the thesis are listed below, projects that featured in the review of practical literature are numbered, practices, case studies undertaken by the author and other shortened titles are given acronyms. The page where the abbreviation is first used is given.

ID	Title	Page
1	Barcelona Fish	83
2	Museum of Tolerance	87
3	Sagrada Familia	81
5	St. Mary Axe	89
6	Sage	86
7	Free University	89
8	Albion Wharf	89
9	Greater London Authority	86
11	Elephant House	85
12	Great Canopy	91
13	Smithsonian Courtyard	85
14	Peek and Cloppenburg	88
15	Mercedes-Benz Museum	92
16	Futuropolis	85
17	Hungerburg Funicular	96
18	Serpentine 2002	81
19	Serpentine 2005	81
20	Taichung Opera	92
21	Bishopsgate Tower	89
22	Nanjing Station	86
23	CSCEC	90

SBM	Seating Bowl Modeller	153
SING	Singapore Domes	184
SMART	Software Modelling Analysis and Research Technology	80
SMG	Specialist Modelling Group	79
WC+CE	William Cox and Clad Engineering	122
WB	Whitby Bird	204
WB1	Planar / twisted panel comparison	210
WB2	Projected grid to doubly curved surface	211
WB3	Spherical patch	211
WB4	Coloured panel analysis	212
WB5	Structural tower	212
WEA	Wilkinson Eyre Architects	199
ZHA	Zaha Hadid Architects	83

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Appendix A

Practice involvement

Project	Dates	Position held by author	Team structure	Activities undertaken by author
Lansdowne Road Stadium	March 06 – Oct 08	Parametric design consultant to architect.	Construction team: Architects HOK Sport. Structural Engineers: Buro Happold. Cladding subcontractors CLAD Engineering.	Parameterisation of planning application. Development of cladding concept. Development of detail design. Coordination with structural design team. Data extraction from model for construction documentation. Coordination and support to cladding subcontractors.
Seating Bowl Modeller	May 07 – Jan 08	Parametric design consultant to architect.	Internal focus group of experienced stadium designers at HOK Sport. Development of stadium seating design tool.	Parametrisation of rules, regulations and logic for stadium seating design. Capture of published design regulations and designer knowledge.
Blackfriars Tower	June 06 – Sept 07	Parametric design consultant to architect.	Architectural design team with integrated parametric designer.	Parameterising proposed tower geometry. Façade design development. Production of models for visualisation. Coordination with computational design of interior.
Moscow Tower	July 06 – Aug 06	Parametric design consultant to façade consultant.	Construction team: Architects RMJM, Structural Engineers: Rambol. Façade design consultants: newtecnic. Façade manufacturer: Shuco.	Parameterising proposed tower geometry. Façade design development. Production of models for visualisation. Coordination with façade manufacturer.
Gazprom Tower	Feb 07 – April 07	Parametric design consultant to façade consultant.	Construction team: Architects RMJM, Structural Engineers: Rambol. Façade design consultants: newtecnic.	Parameterising proposed tower geometry. Façade design development. Production of models for visualisation.
Singapore Domes	Nov 07 – Dec 08	Assistant to geometry and structural design consultant.	Construction team: Architects Wilkinson Eyre. Structural Engineers Atelier One. Geometry and structural design consultant Chris Williams.	Processing structural data formats. Structural analysis

Figure A.1: Author's involvement in practice.

Appendix B

Major workshops

Major parametric design workshops for professionals

Hamiltons	2008	Dec
Ian Simpson Architects	2008	Sept
Whitby Bird	2007	Sept
HOK Sport	2007	June
Marks Barfield	2005	March

Major parametric design workshops at academic institutions

Cap d'Estudis E.T.S.A. del Vallès **Barcelona**	2009	June
ASCAAD conference, **Bahrain**.	2009	May
TU **Berlin**	2009	March
Politecnico di Torino, **Turin**	2009	April
School of the Built Environment, University of **Nottingham**	2009	April
Tallin School of Architecture Estonia	2009	Jan
Manchester School of Architecture	2008	Nov
Warsaw Institute of Technology	2008	Oct
Faculty of Architecture. Politetecnico di **Madrid**	2008	Oct
Antwerp, eCAADe conference	2008	Sept
Politetecnico di **Milan**	2008	March
Royal Danish Academy of Fine Arts, **Copenhagen**	2006-2008	8 workshops
Architectural Association, **London**. Diploma 7	2006	June
Architectural Association/ University of Westminster / UCL	2006	June
Politetecnico di **Torino**	2006	April
KTH, **Stockholm**	2005	Dec
Landscape Urbanism, Architectural Association	2005-2006	2 workshops
Emergent Technologies, Architectural Association	2005-2006	3 workshops
Aarhus School of Architecture	2005	Dec
TU **Delft**	2005	Nov
Lisbon, Portugal eCAADe conference	2005	Sept
TU **Vienna**	2005	Sept
SmartGeometry workshops	2005-2009	

Figure B.1: Workshops given by author.